GEOPHYSICS

VOL. XXIII, NO. 1 JANUARY, 1958

The Moveout Filter ..... *Carl H. Savit, John T. Brustad, and Joseph Sider* 1
Transient Behavior of Patterns ..... *J. E. White* 26
A Review of Methods of Filtering Seismic Data ..... *Mark K. Smith* 44
Seismic Reflection Records Obtained by Dropping a Weight ..... *Edwin B. Neitzel* 58
Directivity Effect of Elongated Charges ..... *A. W. Musgrave, G. W. Ehlert, and D. M. Nash, Jr.* 81
Frequency Analysis for Gravity and Magnetic Interpretation ..... *William C. Dean* 97
Response of Dyke to Oscillating Dipole ..... *James Paul Wesley* 128
Response of Thin Dyke to Oscillating Dipole ..... *James Paul Wesley* 134
Discussions on "A Theoretical Study of Induced Electrical Polarization" .....
..... *James R. Wait, Richard H. Frische, and Haro von Buttlar* 144
A Slide Rule for Near-Surface Refraction Problems ..... *W. A. Knox* 154

DEPARTMENTS

Patents 164
Reviews and Publications Received 172
Memorial
Weston Cawthorne Kimball ..... *A. L. Ladner* 177
Contributors 179
Society Round Table
Committees 184
Local Sections 185
Membership Applications Received 187
Announcements 187
Personal Items 190
Calendar of Meetings 192

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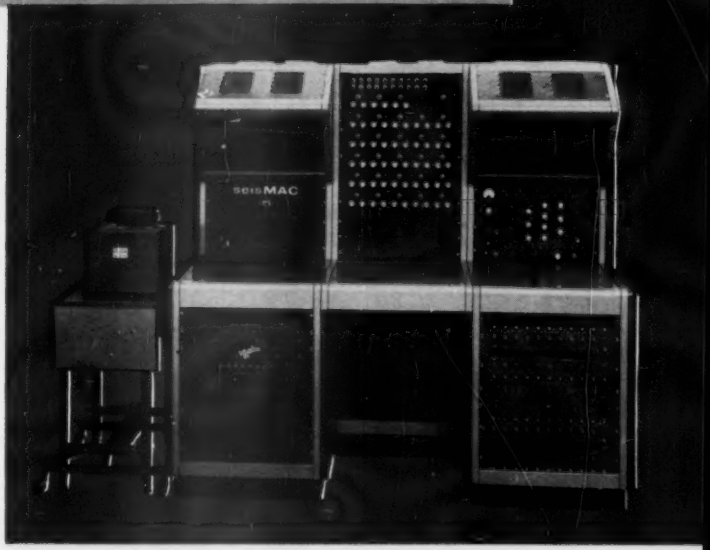

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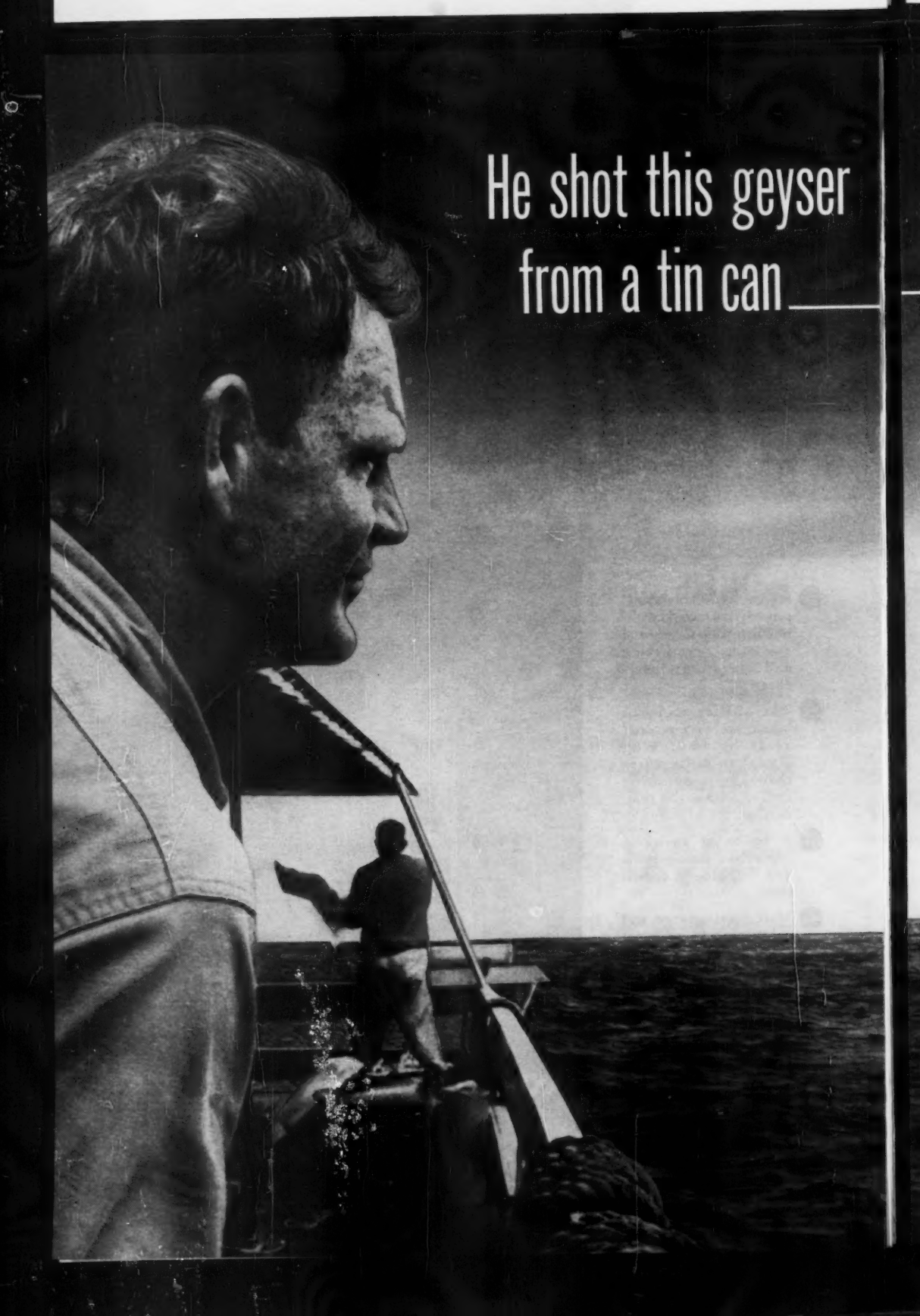
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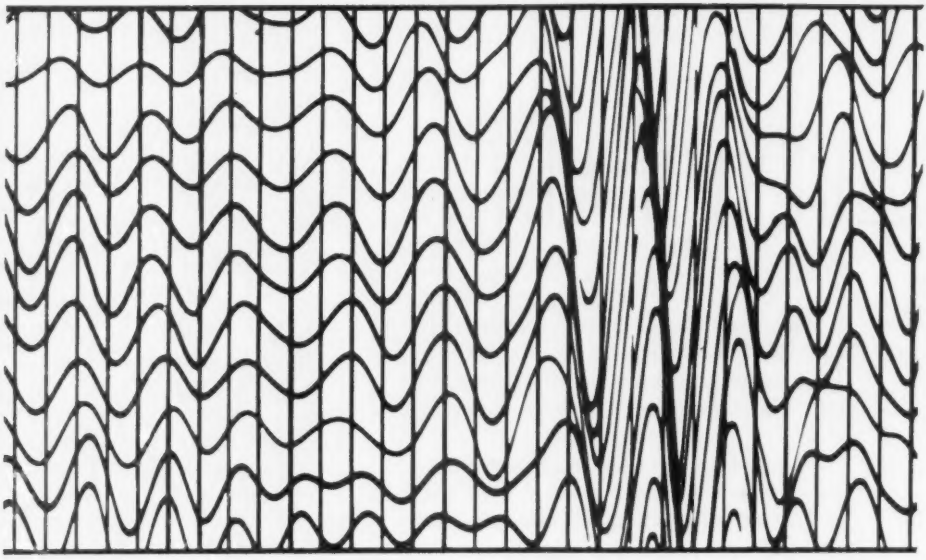

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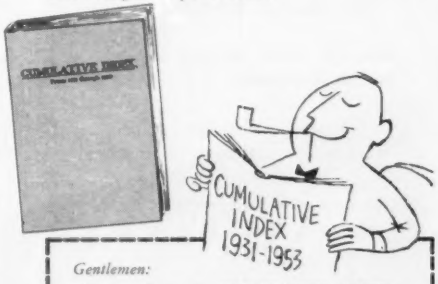

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Electrodynamic Instrument Corp. ... 40
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(See Mandrel Industries)

Fairchild Aerial Surveys, Inc. 32
Fortune Electronics, Inc. 44

General Geophysical Co. 31
Geophysical Associates International 56
Geophysical Integrators, Inc. 12
Geophysical Service, Inc. .....*4th cover*
Geophysical Society of Tulsa 42
Gravity Meter Exploration Co. .....
.....*Insert facing text page 1*
Griffin Tank & Welding Service ....
.....*Insert facing page 53*

Harrison Equipment Co. 54
Herb J. Hawthorne, Inc. 4
Hercules Powder Co. 46

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Klaus Exploration Co. 41
Koenig Iron Works, Inc. 29

Mandrel Industries *15, 62*
Mayes-Bevan Co. 37
Mayhew Supply Co., Inc. .....
.....*Insert facing page 52*
E. V. McCollum & Co. 61
McCollum Exploration Co. 43
Mid-Continent Geophysical Co. 51
Mission Manufacturing Co. .....
.....*Insert facing page 16*

National Geophysical Co. .....*2nd cover*

Oklahoma Geophysical Co. 11
Olsen Seismograph Supplies, Inc. .. 26
Oxley Co. 50

Robert H. Ray Co. 55
Rayflex Exploration Co. 27
Republic Exploration Co. 45
Rogers Geophysical Co. 47
Ruska Instrument Corp. 60

SEG 67
Schlumberger Well Surveying Corp. 57
Seismic Engineering Co. 28
Seismic Explorations Inc. 53
Seismograph Service Corp. ....*3rd cover*
Société d'Etudes Pétrolières 64
Southern Geophysical Co. 49
Southwestern Industrial Electronics
Co. .....*Insert facing page 44*
Spang & Co. 67
Strawn Merchandise Co. 52

Tex-Tube, Inc. 58
Texas Instruments Inc. .....
.....*Insert facing page 60*
Texas Seismograph Co. 24
Tidelands Exploration Co. 33
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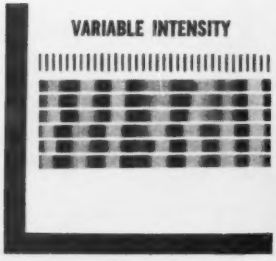

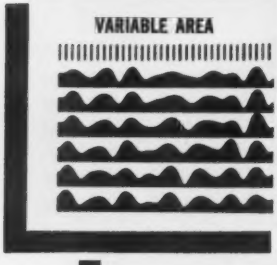

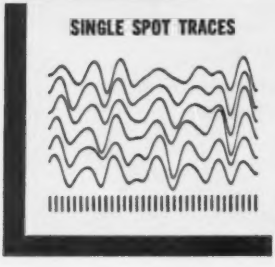

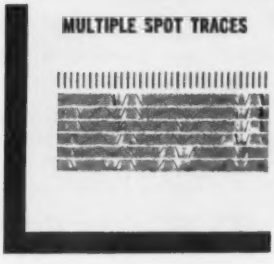

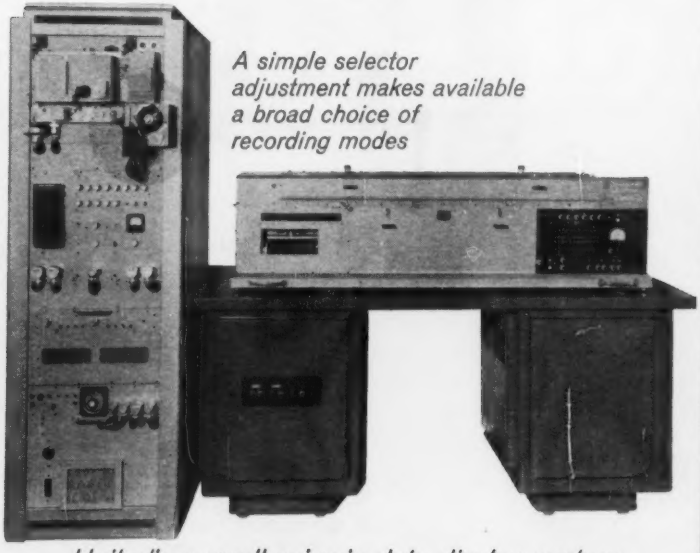

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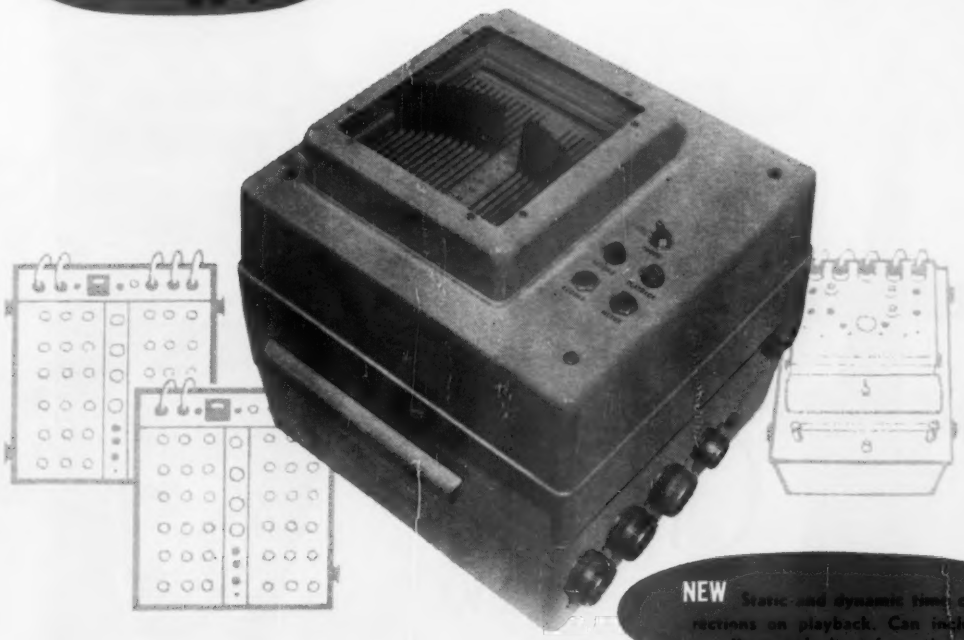

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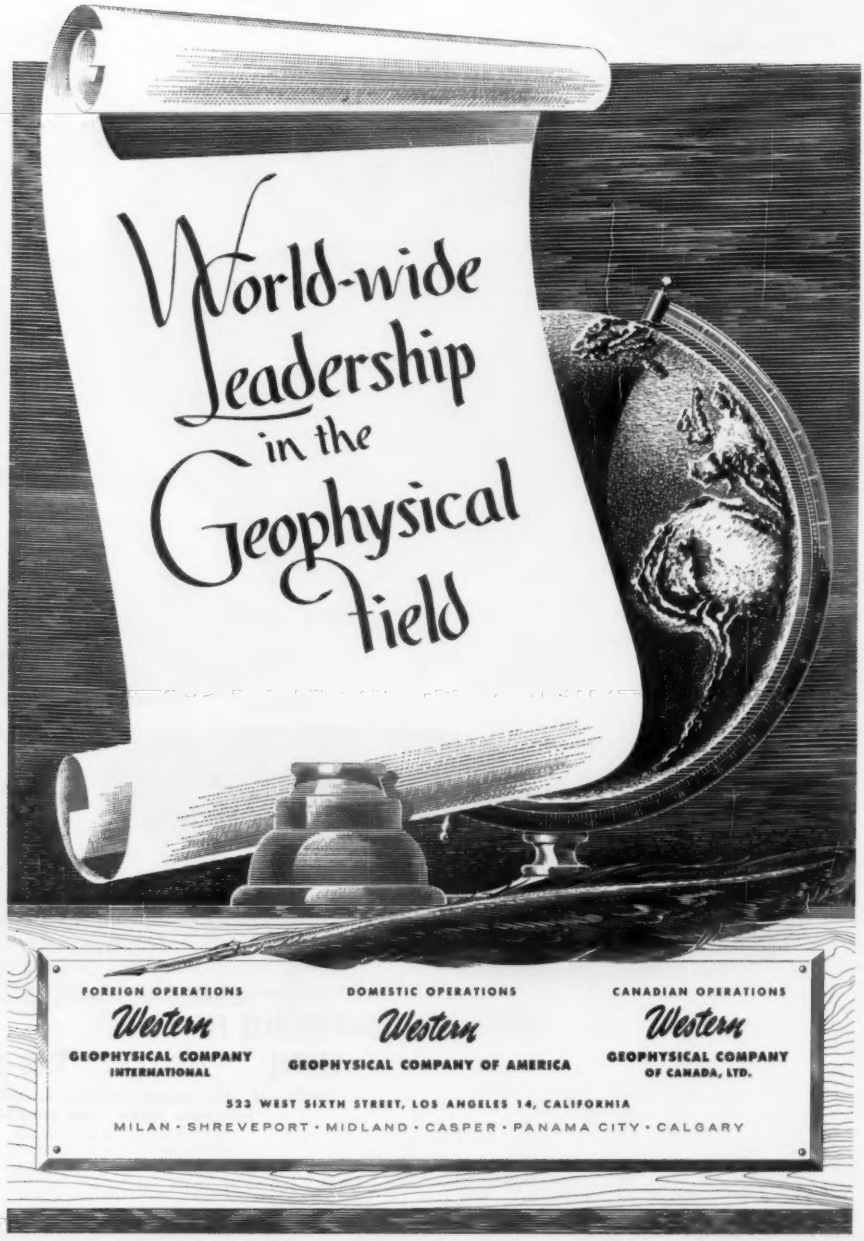
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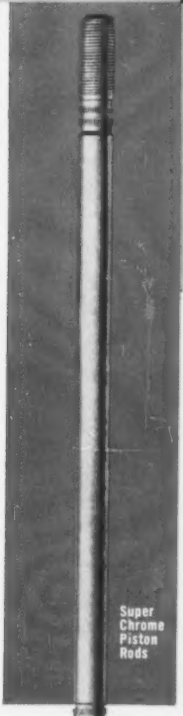

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GEOPHYSICS

THE MOVEOUT FILTER*

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ABSTRACT

The response of a seismometer array or "pattern" is a function of the wave length (also of the moveout or phase velocity) of incident energy. Patterns are thus "moveout filters." The present paper develops the general theory of arrays and gives an explicit solution for the design of an array having a predetermined moveout response.

It is further shown that the antenna theory approach to pattern design is inadequate in the seismic case by reason of the non-uniqueness of the velocity of incident energy.

An example of a pattern designed to meet specific requirements is exhibited. The case presented effects a calculated improvement of at least four to one in signal-to-noise ratio over conventional patterns. The output of the designed system for a horizontally traveling, transient pulse input is shown to be greatly reduced in peak amplitude.

Results of experimental and production use of the moveout filter are presented and discussed.

INTRODUCTION

Reflection seismograph exploration since its inception has been dependent for its very existence on the ability of special instrumentation and techniques to suppress unwanted "noise." Reflected seismic energy is generally so weak as to be completely undetectable against the ever present background of other body waves, surface waves, "wind" noise, and other extraneous motion. In the early days of reflection surveying it was, however, discovered that reflected signals often possessed properties which could be used to distinguish them from the "noise." The first and most important noise suppressor was the electrical filter.

In most areas reflected signals have frequency spectra which are substantially different from those of the noise. Surface waves or "ground roll" were found to be concentrated in the lower portion of the frequency spectrum while the wind and other background noise were generally in the higher frequencies. Fortunately, reflected signals were predominantly characterized by the intermediate frequencies so that simple band-pass filters were highly effective in improving the signal-to-noise ratio.

Band-pass seismograph filters have advanced in design through the years. As electronics progressed from crude beginnings, it became possible to achieve filters to fit almost all special cases.

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Despite the high degree of frequency resolution achievable with present day seismograph instruments, there still remain many areas in which usable seismograms cannot be obtained. Many of these areas are characterized by the presence of high velocity materials at or immediately below the surface. It has been found from field measurements that surface and extraneous body waves in such areas have frequency spectra which are similar to, or which include those of, the reflected signals. Clearly, then, if reflected energy cannot be distinguished from noise on the basis of frequency, conventional electrical filters can effect no improvement in signal-to-noise ratio.

Empirically it has, however, been noted that the use of multiple detectors and multiple shotholes in difficult areas has made a significant improvement in signal-to-noise ratio.

Multiple seismometers are today in general use in reflection seismograph prospecting. A patent covering the use of multiple seismometers was issued in April, 1931, to H. G. Taylor (1931), based on an application filed in 1928. As early as the first months of 1931, two seismometers per trace had been introduced into regular production work by at least one operator. By 1938 multiple seismometers were in general, but somewhat controversial, use (Weatherby, 1940). Increases from the now standard three seismometers per trace to 24 or 36 per trace have yielded useful improvements in signal-to-noise ratio. Many present day prospects, particularly in West Texas, are worked exclusively with 24 or more detectors per trace and as many shotholes in a "pattern."

It is well known that multiple arrays of seismometers and shots have phase velocity discrimination properties and hence directional sensitivity. An analysis of the noise discrimination properties of arrays based on this directivity was published as early as 1936 by Klipsch. In recent years a considerable amount of work has been done on directional properties of arrays from several different viewpoints including particularly the statistical approach of Klipsch, wave-length-phase-velocity analyses, and antenna-theory analogues.

It will be the purpose of this paper to develop the general theory of the directional properties of arrays and to offer an explicit solution to the design problem for arrays of specified directivity.

THE PROBLEM

A seismic disturbance arriving at an instrument array does not, in general, reach each detector in the array at the same instant. The terms "moveout" or "stepout" have been variously used to describe the time difference between corresponding phase points of a disturbance at different spatial locations. For the purposes of this discussion, moveout will be considered to be expressed in units of time per unit of distance. Moveout, thus defined, is the reciprocal of the phase velocity.

Clearly all reflected seismic signals will arrive at the earth's surface with moveouts ranging from zero to a maximum value depending on local dip and

velocity and in no event with a moveout greater than the reciprocal of the subweathering velocity. On the other hand, it is certainly possible that seismic noise will have moveouts larger than the maximum set for reflections. High moveouts are certainly to be expected of surface waves, shear waves, and air blast. Since it is, in general, true that the "*P*" wave travels faster than all other waves, it may be concluded that horizontally traveling noise other than "*P*" wave noise will have lower phase velocities and hence higher moveouts than will reflections. In many areas these conclusions have been amply verified by direct observation and experiment.

It now follows that the properties of moveout are analogous to those of frequency in that moveout distributions may be likened to frequency spectra. Seismic signals and seismic noise have different moveout distributions just as they have different frequency spectra. Significant improvement should, therefore, be expected in signal-to-noise ratio through the use of any device which discriminates against noise moveouts. Such a device may aptly be termed a "moveout filter."

When the nature of the seismic disturbance is expressed in terms of both time and space coordinates, the analogy between frequency and a quantity related to moveout is particularly striking. All realizable seismic disturbances arriving at a line on the surface of the earth may be expressed as a double sum (finite or infinite) of components of the form $A_{p,n} \sin (2\pi\omega_p t + 2\pi\alpha_n x + \beta_{p,n})$ where $A_{p,n}$ is the amplitude, ω_p is the frequency, α_n is the reciprocal wave length (spatial frequency) and $\beta_{p,n}$ is the phase angle of the component. Time and location of the observation measured from arbitrary origins are expressed as t and x respectively. It is immediately evident that α_n bears the same relation to x as ω_p bears to t. That is, the conventional time frequency and spatial frequency are mathematically indistinguishable.

Moveout having been defined as time difference per unit distance, it follows that moveout times frequency is the reciprocal of wave length, the quantity which we have termed the spatial frequency. For any given time frequency, then, a given moveout corresponds to a unique spatial frequency and vice versa.

From the previous discussion it follows that, theoretically, it is desirable to incorporate within a seismograph system a low pass moveout filter. Such a filter would pass low moveouts, that is low values of spatial frequency, and reject the higher moveouts.

CONVENTIONAL ARRAYS

A study of the moveout discrimination properties of arrays was undertaken for the purpose of determining to what extent conventional arrays were functioning as moveout filters and to what extent such filtering could be improved.

With respect to any plane wave front, a two-dimensional group of detectors will be equivalent to a one dimensional group in a plane perpendicular to that wave front. The discussion will therefore be limited to one-dimensional arrays.

A signal (or noise) arriving at a finite point x, $0 \leq x \leq X$, and having a finite duration $0 \leq t \leq T$, can be expressed in the form

$$\sigma = \sum_{n=1}^{\infty} \sum_{p=1}^{\infty} A_{p,n} \sin (2\pi\omega_p t + 2\pi\alpha_n x + \beta_{p,n}) \tag{1}$$

where $\omega_p = p/T$ and $\alpha_n = n/X$. ω_p is the time frequency and α_n is the spatial frequency.

The quantity $\lambda_n = 1/\alpha_n$ is the wave length just as $\rho_p = 1/\omega_p$ is the period of a component. The phase velocity of a signal component along the array is given by $v_{p,n} = \omega_p \lambda_n$ and varies with the nature and direction of the incident signal.

Consider a single component $\omega_p = \omega$ and $\alpha_n = \alpha$ with $\beta_{p,n} = \beta$. Then for a uniformly distributed array of $m+1 = M$ elements over an interval of length S, the signal output at the time frequency ω and spatial frequency α will be of the form

$$\frac{1}{m+1} \sum_{k=0}^{m} \sin\left(2\pi\omega t + \beta + 2\pi \frac{k}{m} \alpha S\right) = \frac{\sin (2\pi\omega t + \beta + \pi\alpha S) \sin\left(\dfrac{m+1}{m} \pi\alpha S\right)}{(m+1) \sin \pi\alpha S/m}. \tag{2}$$

Thus it is apparent that the output of the group is a sinusoidal signal of frequency ω, whose amplitude is

$$A_M = \left| \frac{\sin \dfrac{m+1}{m} \pi\alpha S}{(m+1) \sin \dfrac{\pi\alpha S}{m}} \right| = \left| \frac{\sin \dfrac{M}{M-1} \pi\alpha S}{M \sin \dfrac{\pi\alpha S}{M-1}} \right|, \tag{3}$$

introducing $\alpha = 1/\lambda$ the amplitude becomes

$$A_M = \left| \frac{\sin \dfrac{M}{M-1} \dfrac{\pi S}{\lambda}}{M \sin \dfrac{1}{M-1} \dfrac{\pi S}{\lambda}} \right|. \tag{4}$$

The response of an infinite number of seismometers arrayed over a length S (equivalently, one continuous seismometer whose length is S) is given by letting M approach infinity.

$$\lim_{M \to \infty} A_M = \left| \frac{\sin \dfrac{\pi S}{\lambda}}{\dfrac{\pi S}{\lambda}} \right| = A_\infty.$$

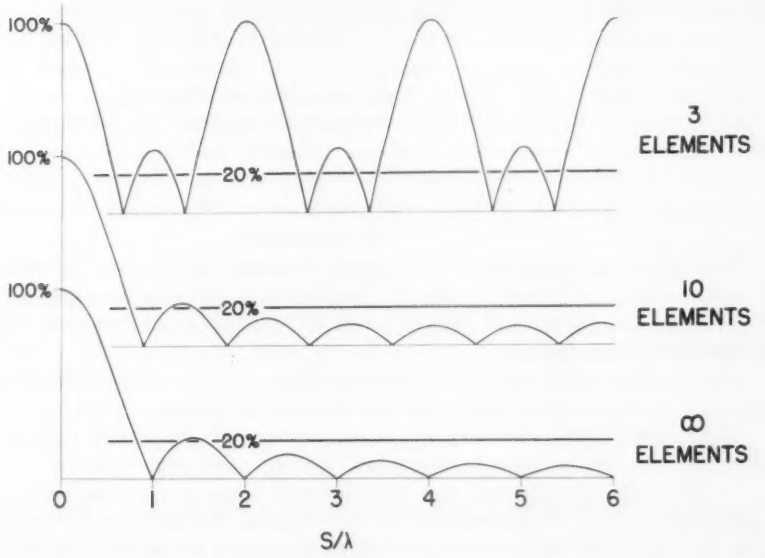

FIG. 1. A comparison of the amplitude as a function of the dimensionless spatial frequency S/λ for arrays of the same total length, but with a differing number of identical elements: 3, 10, and an infinite number. The amplitude is an even, periodic function of S/λ for groups with a finite number of elements, the periods of the three-element and ten-element groups being two and nine respectively.

Figure 1 shows A_3, A_{10}, and A_∞. It will be noted that the A_M are normalized on the basis that for all M, $\lim_{\lambda\to\infty} A_M = 1$.

It is thus seen that increasing the value of M, the number of seismometers in the array, beyond about ten can yield no appreciable improvement in moveout (or phase velocity) discrimination if all seismometers have equal output and are uniformly spaced, provided the amount of noise corresponding to values of $S/\lambda > 8$, is negligible.

NON-UNIFORM ARRAYS

The most general types of linear arrays may be described by a weight function $f(x)$ which gives the contribution of the array to the total output from any point of coordinate x.

Thus the output of such a system in response to the input

$$\cos\,(2\pi\omega t + 2\pi\alpha x + \beta)$$

is given by

$$\int_{-\infty}^{\infty} \cos\,(2\pi\omega t + 2\pi\alpha x + \beta) f(x)\,dx. \tag{5}$$

(In order to take into account finite groups of isolated detectors, the integrals in this section should be considered in the Lebesgue-Stieltjes sense and the notation $f(x)dx$ should be considered equivalent to the notation $dF(x)$ where $F(x)$ will, for our purposes, be a stepwise continuous, bounded function.)

For simplicity of treatment we shall normalize our results by restricting $f(x)$ such that

$$\int_{-\infty}^{\infty} f(x)dx = 1. \tag{6}$$

This restriction is equivalent to using the response of the array to arrivals of zero moveout (infinite phase velocity) as the unit of measure for response.

It is now possible to state the conditions which must be satisfied by an ideal moveout discriminating array.

The incoming signal will be presumed to consist of components within a narrow band of frequencies ω (due perhaps to filtering) such that, $\omega_1 < \omega < \omega_2$.

The "signal" will be assumed to possess a phase velocity v such that $v_1 < v$, while the noise will be taken to have phase velocity v such that $v < v_2 < v_1$.

It will further be assumed that there exists a value α_0 such that $\omega_2/v_1 \leq \alpha_0 \leq \omega_1/v_2$, that is, that the desired pass and reject bands on α (or λ) do not overlap. That the probability of the validity of this assumption is increased by narrowing the filter pass band is immediately evident.

In the present discussion we shall further limit ourselves to symmetrical arrays. Antisymmetric arrays can be considered by appropriate substitution of co-functions for the trigonometric functions. A general array can be expressed as a combination of a symmetric and an antisymmetric part. It is further to be noted that practical considerations render symmetrical arrays preferable to non-symmetrical arrays provided the desired properties can be procured reasonably well. We shall, therefore, treat only the case where $f(x) = f(-x)$. Whence (5) becomes after substituting (6):

$$\int_{-\infty}^{\infty} \cos(2\pi\omega t + 2\pi\alpha x + \beta) f(x)dx = 2\cos(2\pi\omega t + \beta) \int_{0}^{\infty} \cos 2\pi\alpha x f(x)dx. \tag{7}$$

The amplitude $A(\alpha)$ of the output is thus given by

$$A(\alpha) = 2\left| \int_{0}^{\infty} \cos 2\pi\alpha x \, f(x)dx \right|. \tag{8}$$

Ideally, then, $A(\alpha)$ should be the function

$$\begin{aligned} A(\alpha) &= 1 \qquad 0 \leq \alpha \leq \alpha_0. \\ A(\alpha) &= 0 \qquad \alpha_0 < \alpha \end{aligned} \tag{9}$$

If $f(x)$ be a continuous function defined everywhere on the positive real axis and since $\int_0^\infty f(x)dx$ exists, (see (6)), it follows that

$$f(x) = 2\int_0^\infty A(\alpha)\cos 2\pi\alpha x d\alpha = 2\int_0^{\alpha_0}\cos 2\pi\alpha x d\alpha = \frac{\sin 2\pi\alpha_0 x}{\pi x}. \quad (10)$$

Investigations were conducted to determine to what degree any function $A(\alpha)$ could be approximated by using a function $f(x)$ which represents a realizable seismometer array. These investigations followed two lines. Seismometer arrays of identical elements on an arbitrary set of points were considered, as were arrays of seismometers of arbitrary sensitivity on a uniformly spaced set of points. The criterion of degree of approximation was chosen to be that of least squares in conformity with evidence brought out in experimental studies. A discussion of this point appears in a later section.

Assume an array of $2n+1$ seismometers of equal output at points $x=0$, $\pm r_1X$, $\pm r_2X$, $\cdots$, $\pm r_nX$. Then the input $\cos(2\pi\omega t+2\pi\alpha x+\beta)$ will produce an output of the form

$$\cos(2\pi\omega t+\beta)B(\alpha; r_1, r_2, \cdots, r_n) = \cos(2\pi\omega t+\beta)\left[1+2\sum_{k=1}^{n}\cos 2\pi\alpha r_k X\right].$$

A least squares best fit for B to the $A(\alpha)$ defined by (9) may be obtained by minimizing

$$\int_0^{\alpha_1}[A(\alpha) - B(\alpha; r_1, r_2, \cdots, r_n)]^2 d\alpha \quad (11)$$

where $\alpha_1 = 1/\Lambda$ and where Λ is the minimum wave length of energy to be rejected.

A set of n simultaneous equations,

$$\int_0^{\alpha_1}\alpha X\sin(2\pi\alpha r_k X)A(\alpha)d\alpha = \int_0^{\alpha_1}\alpha X\sin(2\pi\alpha r_k X)B(\alpha; r_1, r_2, \cdots, r_n)d\alpha \quad (12)$$

must be solved.

Various approximate solutions were obtained but proved to be inferior to the exact solutions obtained for the equal spacing, arbitrary sensitivity cases described below. The further consideration that variable spacing methods were not practicable for field use led to the abandonment of this approach.

The other approach which was investigated was the use of $2n+1$ detectors of arbitrary sensitivity at locations $x=0$, $\pm X/n$, $\pm 2X/n$, $\cdots$, $\pm X$ whose sensitivities are given by 1, a_1, a_2, $\cdots$, a_n. Again the input is considered to be $\cos(2\pi\omega t+2\pi\alpha x+\beta)$ and the output now becomes

$$\cos(2\pi\omega t+\beta)C(\alpha; a_1, a_2, \cdots, a_n) = \cos(2\pi\omega t+\beta)\left[1+2\sum_{k=1}^{n}a_k\cos\frac{2\pi\alpha k X}{n}\right]. \quad (13)$$

In order to normalize C, define

$$C' = \frac{1 + 2\sum_{k=1}^{n} a_k \cos \frac{2\pi\alpha k X}{n}}{1 + 2\sum_{k=1}^{n} a_k} \tag{14}$$

or equivalently

$$C' = q_0 + 2\sum_{k=1}^{n} q_k \cos \frac{2\pi\alpha k X}{n} \tag{15}$$

where

$$q_k = \frac{a_k}{1 + 2\sum_{j=1}^{n} a_j}$$

and

$$q_0 = 1 - 2\sum_{j=1}^{n} q_j.$$

The least squares optimum values of q_k are given by minimizing the integral

$$\int_{-\alpha_1}^{\alpha_1} [A(\alpha) - C'(\alpha; q_1, q_2, \cdots, q_n)]^2 d\alpha. \tag{16}$$

If for α we choose the value $n/2X$, the q_k are related to the Fourier coefficients in the cosine expansion of $A(\alpha)$.

Differentiating (16) and equating to zero, we obtain the n equations

$$\int_{-n/2X}^{n/2X} [A(\alpha) - C'(\alpha; q_1, q_2, \cdots, q_n)]\left[\cos \frac{2\pi\alpha k X}{n} - 1\right] d\alpha = 0 \tag{17}$$

whence by rearrangement

$$\int_{-n/2X}^{n/2X} A(\alpha)\left[\cos \frac{2\pi\alpha k X}{n} - 1\right] d\alpha = q_k \frac{n}{X} + \frac{n}{X}\left(-1 + 2\sum_{j=1}^{n} q_j\right) \tag{18}$$

so that

$$q_k = \frac{X}{n}\int_{-n/2X}^{n/2X} A(\alpha)\left[\cos \frac{2\pi\alpha k X}{n} - 1\right] d\alpha \quad + \left[1 - 2\sum_{j=1}^{n} q_j\right]. \tag{19}$$

If now (19) be summed over k, the resulting sum may be substituted into the

right hand side of (19) to obtain

$$q_k = \frac{X}{n}\int_{-n/2X}^{n/2X} A(\alpha)\cos\frac{2\pi\alpha kX}{n}\,d\alpha + \frac{1}{1+2n}\left[1 - \frac{X}{n}\int_{-n/2X}^{n/2X} A(\alpha)d\alpha - 2\sum_{j=1}^{n}\frac{X}{n}\int_{-n/2X}^{n/2X} A(\alpha)\cos\frac{2\pi\alpha jX}{n}\,d\alpha\right]. \tag{20}$$

A Twenty-One Element Moveout Filter

From calculations it was observed that for a given number of seismometers the most useful results were obtained when all the q_k were positive. Since the maximum wave length which can be completely filtered out under these conditions cannot exceed the group length, the minimum length of the group is dictated by the maximum wave length which it is desirable to have filtered out.

Since $C(\alpha; q_1, q_2, \cdots, q_k)$ is a periodic function of α, the spacing of the seismometers must be such that the 100 percent response peaks which occur after $\alpha = 0$ will not correspond to wave lengths that are associated with substantial energy. The first peak will occur at a value of α corresponding to a wave length equal to the seismometer spacing in the group. The only source of energy that it was felt desirable to exclude at these smaller wave lengths was the air blast, whose wave length for 30 cycle to 50 cycle frequencies ranges from 37.7 to 22.6 feet.

In view of the above considerations, calculations were made for a group of 21 elements (i.e., $n = 10$) with a spacing of 20 feet. $A(\alpha)$ was defined as follows:

$$A(\alpha) = 1 \qquad 0 \le |\alpha| \le \frac{n}{24X} = \frac{5}{12X}$$

$$A(\alpha) = 0 \qquad |\alpha| \ge \frac{n}{24X} = \frac{5}{12X}.$$

The resulting q_k are:

TABLE I

$q_1 = 0.987$	$q_6 = 0.592$
$q_2 = 0.947$	$q_7 = 0.473$
$q_3 = 0.888$	$q_8 = 0.348$
$q_4 = 0.809$	$q_9 = 0.224$
$q_5 = 0.704$	$q_{10} = 0.105$.

Figure 2 compares the calculated amplitude curve as a function of S/λ for the 21 element array using these q_k with an array of the same number of elements having equal sensitivities. Arrays of elements of unequal sensitivities have been termed tapered arrays, since in most applications sensitivities grade from a maximum at the center to small values at both ends.

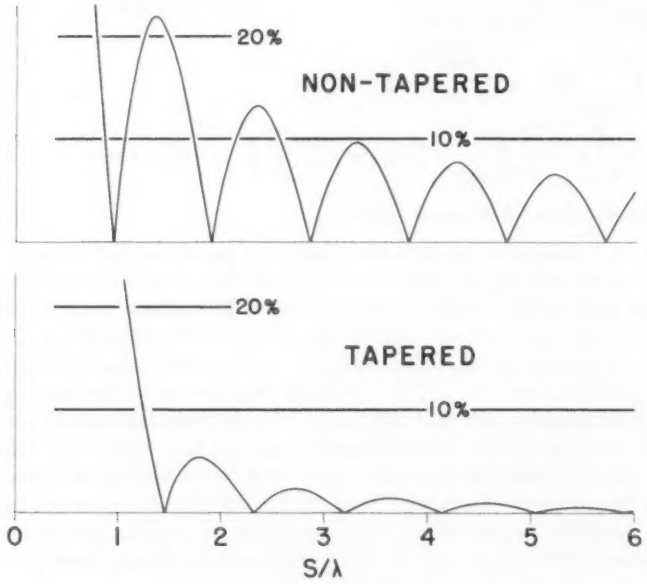

FIG. 2. A comparison of the amplitude as a function of S/λ between two twenty-one-element, equally-spaced arrays, identical except for the sensitivities. The sensitivities of the elements in the tapered array are listed in Table I; the sensitivities of the elements in the non-tapered array are all equal.

Using the conventional antenna theory approach, the same two response relationships may be compared in polar coordinates as shown in Figure 3. Since the curve for the non-tapered group response has a node and secondary lobes, some signal loss as well as inversion for near horizontal arrival may be expected contrary to the situation for the tapered group. Such a plot does not afford an opportunity to examine the response of a system to moveouts greater than that of the horizontal "*P*" wave. The polar graph represents only that portion of the spatial frequency plot for which S/λ is less than $1\frac{1}{3}$. It is precisely in the region of the higher spatial frequencies, however, that the bulk of the noise to be rejected lies. It follows that this type of plot is not suited to the study of the noise-rejecting properties of multiple seismometer groups.

The effect of the tapered array on transients was investigated. The outputs of these same two 21 element arrays in response to a transient wavelet were calculated using a horizontal phase velocity of 12,500 feet per second (moveout 8 ms/100 ft). Figure 4 shows the input transient and the two calculated output transients. The peak amplitudes of the outputs for the tapered and non-tapered arrays were in the ratio 1:2.2. It was anticipated that the results of this calcula-

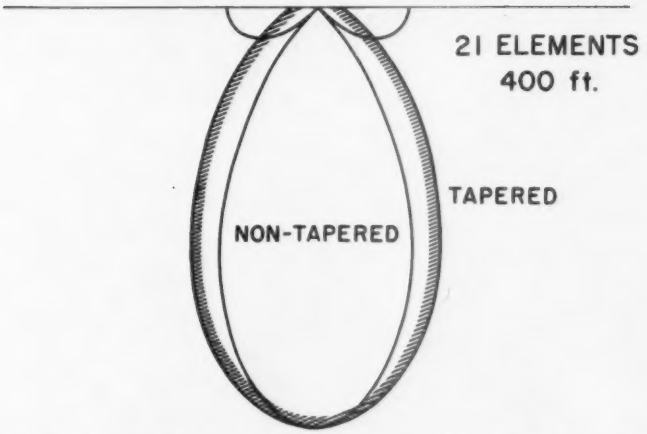

FIG. 3. A comparison of the non-tapered and tapered arrays shown in Figure 2 plotted in polar coordinates in the manner conventionally used in antenna theory. This plot is equivalent to that portion of Figure 2 representing values of S/λ from zero to 1.33.

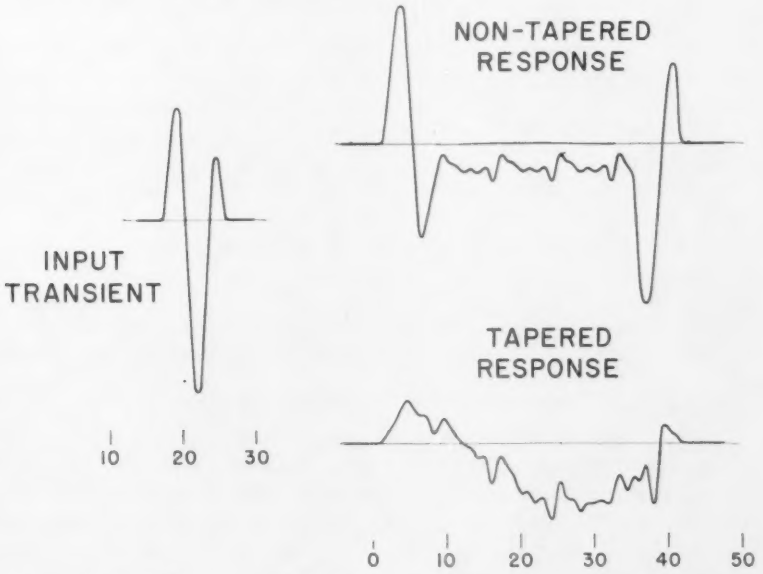

FIG. 4. The outputs of a tapered (see Table I) array and a non-tapered array, each of 21 elements, in response to an input transient wavelet moving with a horizontal velocity of 12,500 feet per second are shown for comparison. The input wavelet is taken from experimental measurements of Ricker (1953, p. 18). Horizontal scales are in milliseconds.

tion would be a guide to the behavior of actual arrays in response to the direct refraction break in areas for which the near-surface refraction velocity is of the order of 12,500 feet per second. Conventional electronic filtering subsequently applied to these outputs should further enhance the contrast between the two responses.

COMPOSITE ARRAYS

The common practice of mixing or compositing the outputs of adjacent arrays (seismometer groups) suggested the study of the phase velocity discrimination properties of mixed or composited recording.

If the output for any one array in response to the input $\cos(2\pi\omega t+2\pi\alpha x+\beta)$ is given by $D(\alpha)\cos(2\pi\omega t+\beta)$, the output for two collinear arrays whose centers are at $x=\pm d$ will be given by

$$\tfrac{1}{2}\left[D(\alpha)\cos(2\pi\omega t-2\pi\alpha d+\beta)+D(\alpha)\cos(2\pi\omega t+2\pi\alpha d+\beta)\right]= D(\alpha)\cos 2\pi\alpha d\cos(2\pi\omega t+\beta). \tag{21}$$

Since A_2 (see (4)) is $\cos \pi S/\lambda$ and $\alpha=1/\lambda$, it is clear that the amplitude response for two compounded arrays is the product of the response curve of each individual array by the response curve of an array of two elements spaced a distance $2d$.

This result may be generalized to the theorem that a meta-array of identical arrays (all arrays being restricted to symmetrical arrays normalized to unit response for infinite phase velocity) will have a response curve equal to the product of the response curve of the typical array by the response curve of the meta-array considered as a simple array.

The way is thus open to the ready calculation of the response curves of composite arrays. Figure 5 is a comparison of the response curve of the 21 element tapered array of Table I with a compounded pair of such arrays. A significant improvement in noise rejection is seen to result from this compounding. The various other mixing and overlap systems studied led to the conclusion that by proper choice of systems used it is possible to achieve response curves having a wide range of characteristics, particularly very narrow "pass" bands.

EFFECTIVENESS OF THE MOVEOUT FILTER

Criteria of the effectiveness of a moveout filter are directly related to the criteria of goodness of fit used in optimizing the filter design. The choice of a least squares best fit for designing the filter implies that it is desired to minimize the root-mean-square output in the reject band. The choice of spatial frequency as the variable of integration in equation (11) implies that substantially equal importance is attached to noise of all spatial frequencies within the range of investigation.

A variable weighting of the seismometers in a group has been discussed previously, in particular, by Parr and Mayne (1955). In their filter the maximum

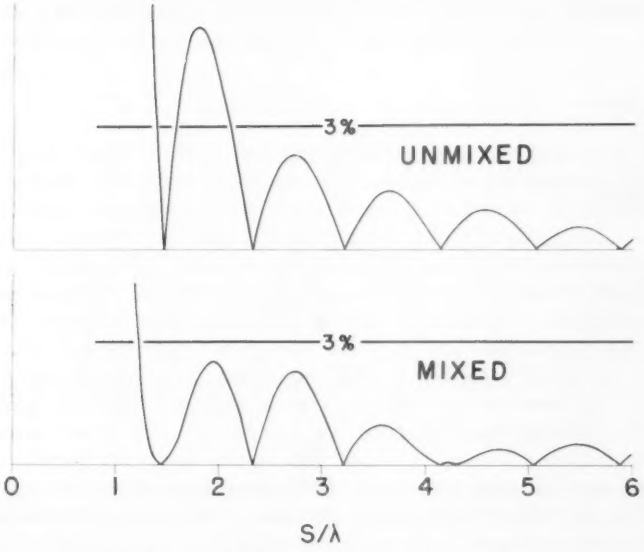

FIG. 5. A comparison of the amplitude as a function of S/λ for the tapered twenty-one-element array (also shown in Figure 2) and for the sum of two such arrays (simple mixing) where the distance between group centers is seven times that between the individual elements.

amplitude in the reject band is minimized in contradistinction to the minimization of the root-mean-square output over the reject band as discussed in the present paper. The superiority of one type of weighting over the other then depends on the noise characteristics prevalent in the area. If the amount of noise, considered as a function of S/λ, were to exhibit several randomly distributed high-amplitude peaks, it might be desirable to construct a filter of the Parr-Mayne type so that the effect of the high-amplitude peaks would be minimized. If however, the amount of noise is uniformly distributed over the reject band, it is then desirable to minimize the root-mean-square output over the reject band. In the areas studied by the authors, the latter situation was more nearly approximated and is discussed later. Further to distinguish between the present system and that of Parr-Mayne it should be noted that the present moveout filter represents a best fit to ideal response over the entire range of interest. That is, the response is made to fit over both the desired pass and reject bands, whereas the criterion applied by Parr and Mayne is that the maximum response in the reject band be minimized while response in the pass band is not controlled. Thus the Parr-Mayne system exerts a control on the absolute level of noise in contradistinction to the control upon the relative level of signal and noise exerted by the moveout filter.

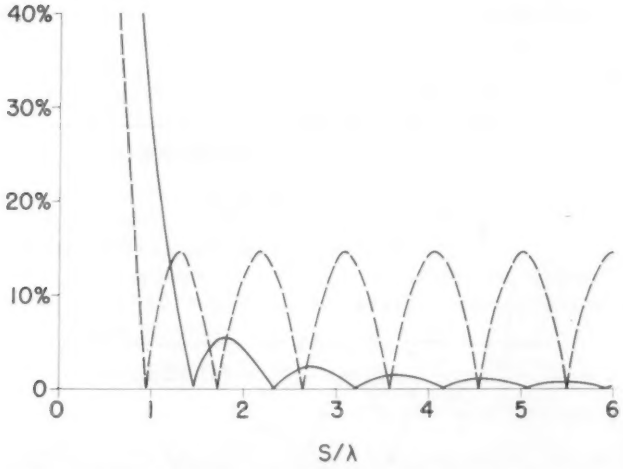

FIG. 6. Comparison between the moveout filter (solid line) and the Parr-Mayne filter (dashed line). Both arrays are calculated for the same design parameters, 21 elements and a common reject band.

A numerical calculation was performed to compare the twenty-one element moveout filter whose weightings are listed in Table I with a Parr-Mayne filter based on the same number of seismometers (21), the same distance apart (20 feet) and using the same reject band ($\lambda_L = 480$ feet, $\lambda_s = 480/23$, $W = 23$). In their notation,

$$\theta_L = \frac{2\pi D}{\lambda_L} = \frac{\pi}{12} \quad \text{and} \quad x = \frac{2}{1 - \cos\theta_L} = 58.696.$$

Based on the center seismometer having unit weight, the weightings at increasing distances from the center are: $E_{10} = 0.993$, $E_9 = 0.973$, $E_8 = 0.940$, $E_7 = 0.895$, $E_6 = 0.840$, $E_5 = 0.775$, $E_4 = 0.704$, $E_3 = 0.628$, $E_2 = 0.548$, $E_1 = 1.609$. The maximum amplitude in the reject band is then 0.144. It is to be noted that the maximum amplitude of the moveout filter in the reject band is 0.447 (at $\theta = \theta_L = \pi/12$, i.e., $S/\lambda = 0.833$), but the next succeeding peak has an amplitude of only 0.055, and all subsequent peaks to the center of symmetry at $\theta = \pi$, ($S/\lambda = 10.0$) are even less than this. It is thus seen that with the exception of a narrow band of wavelengths near $\lambda = 480$ and at the nodes, the filtering effect of the moveout filter over the reject band is much greater than that of the Parr-Mayne array (Figure 6).

Studies of pickable noise patterns in several areas indicate that such noise tends to be fairly uniformly distributed over a moveout range from the moveout of horizontally traveling "*P*" waves to some upper value depending on local

conditions, and then it declines. It should also be noted that the duration τ of the disturbing effect of a noise transient on a given trace of a seismogram is given by the equation

$$\tau = (S + L)/v = S/v + L/v = MS + T \qquad (22)$$

where S is the length of the detector group contributing to the trace, L, M, and T are respectively the length, moveout, and duration of the transient. (L and T are considered to be measured between threshold points of the transient, L is measured at a fixed time, while T is measured at a fixed point.)

It is thus clear that higher moveout noise affects a larger proportion of each trace and indeed of the whole seismogram than does lower moveout noise. This increased disturbing effect at higher moveouts counteracts the decline in frequency of occurrence of the higher moveout noise. The valid range of the assumption of substantially equal importance of noise of all spatial frequencies may thus be extended beyond the range of constant frequency of occurrence.

The role of S in the equation (22) indicates that large detector groups may have an adverse effect if the noise is not attenuated below threshold by the filtering effect of the group. An adverse effect produced by increasing the number of detectors beyond one has been observed under actual field use in at least one instance by the authors. An independent observation of similar nature has been reported by Dr. George Shor of the Scripps Institution of Oceanography in a private communication. In these cases the noise was found to consist of relatively infrequent bursts of large amplitude and short duration.

Areas in which the moveout filter concept has been and is being applied are characterized by noise systems fairly uniform both in order of magnitude of noise amplitude and in distribution over the moveout spectrum. For such situations the least squares best fit criterion and the choice of spatial frequency as the variable of integration appear to be reasonable.

For a typical area there has been plotted in Figure 7 the frequency of occurrence of pickable persistent wave trains of both reflections and noise as a function of the spatial frequency. The graph represents the composite results of many individual observations and is effectively a spectrum for spatial frequencies of the noise and signal as seen by instruments passing time frequencies from 20 to 70 cycles per second and with one seismometer per trace (i.e., with no moveout filtering). Signal-to-noise ratio is here defined as the ratio of the areas under the signal and noise spectrum curves.

Figures 8 through 12 show successively the effect of applying electronic band pass filtering and of various moveout filters. The moveout filters considered are a three detector group on 100 feet, a group of infinitely many detectors on 200 feet, 21 equal detectors on 400 feet, the 21 element tapered 400 foot group of Table I and the 21 element Parr-Mayne array, Figure 13. In preparing these illustrations, it has been assumed that the amplitude of a signal or noise event is directly proportional to its probability of detection on a seismogram. The value

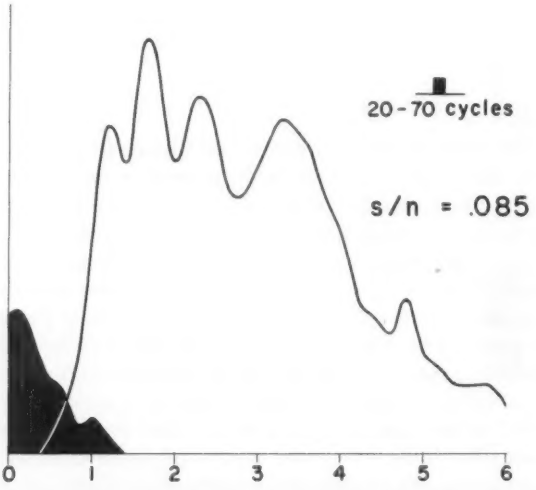

FIG. 7. Signal and noise spectra for a test area plotted on a scale of S/λ. The signal spectrum is shown as a solid area while the noise spectrum is shown in outline. This determination represents observations in a frequency range of 20 to 70 cycles per second using one seismometer per trace. The signal-to-noise ratio is 0.085.

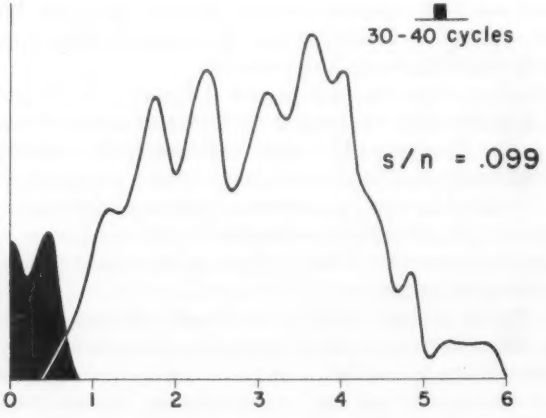

FIG. 8. A comparison of the signal and noise spectra shown in Figure 7 but with the energy having been filtered through a conventional filter with a pass band of 30 to 40 cycles per second. The signal-to-noise ratio is improved to 0.099.

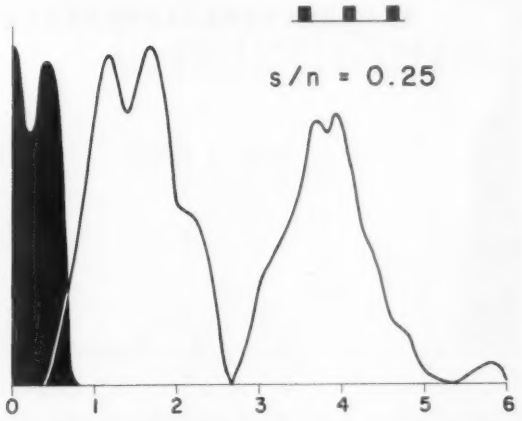

FIG. 9. The signal and noise spectra shown in Figure 8 as modified by moveout filtering consisting of 3 seismometers per group on a group length of 100 feet. The signal-to-noise ratio is now 0.25.

of S has been held constant at 400 feet in this series of illustrations in order that all scales shall be comparable. Marked, progressive improvement in signal-to-noise ratio is observed as the moveout filtering is improved. This improvement is summarized in Figure 14.

Mixing or compounding further improves the signal-to-noise ratio, as shown in Figures 15 and 16. Extremes of moveout filtering as shown in Figure 16 can

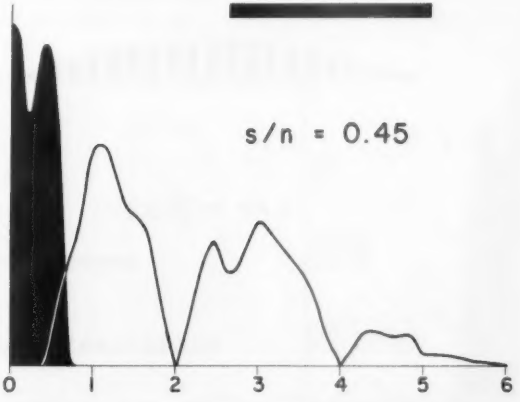

FIG. 10. The same signal and noise spectra but with moveout filtering now consisting of a seismometer group 200 feet in length comprised of an infinite number of seismometers. This corresponds to the maximum improvement possible with unweighted seismometers over this group length. The signal-to-noise ratio is now 0.45.

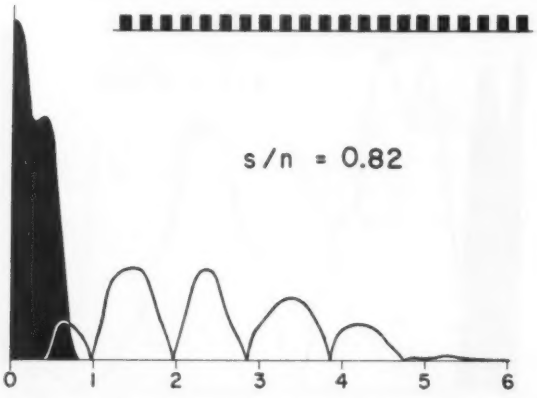

FIG. 11. The same signal and noise spectra as seen through a group length of 400 feet with 21 unweighted seismometers per group. The signal-to-noise ratio is 0.82.

result in a significant loss of signal while, nevertheless, improving signal-to-noise ratio. It is thus suggested that extremely sharp moveout filters be reserved for those prospects in which useful results cannot otherwise be obtained.

Field tests of linear tapered arrays have been conducted in selected areas. Tests in those areas which had been found to have large amounts of high moveout noise produced results in good agreement with theory. Linear tapered arrays were found in many cases to yield records distinctly superior to those obtained with conventional areal arrays of multiple seismometers.

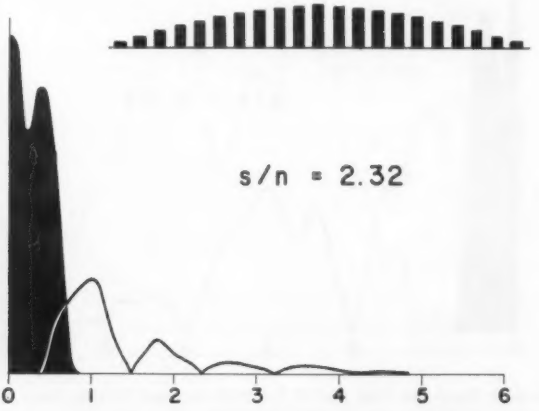

FIG. 12. The same signal and noise spectra with the tapered group (see Table I) of 21 elements over 400 feet. The signal-to-noise ratio jumps to 2.32.

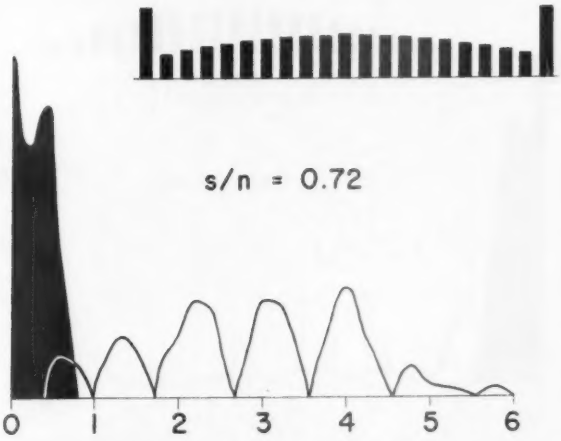

FIG. 13. Signal and noise spectra of Figure 8 as seen through the Parr-Mayne 21-element filter whose response characteristics are shown in Figure 6. The signal-to-noise ratio is 0.72.

Portions of several field records are shown in Figure 17 (a, b, c, d, e). These are direct comparisons between 21 element linear tapered arrays and 36 and 20 element stars.

Comparisons between tapered and non-tapered linear arrays were conducted on several field parties. A total of more than two crew-years of experience in which a tapered and a non-tapered cable of identical dimensions were alternated, is now available. Results with the two cables were very nearly the same. Occa-

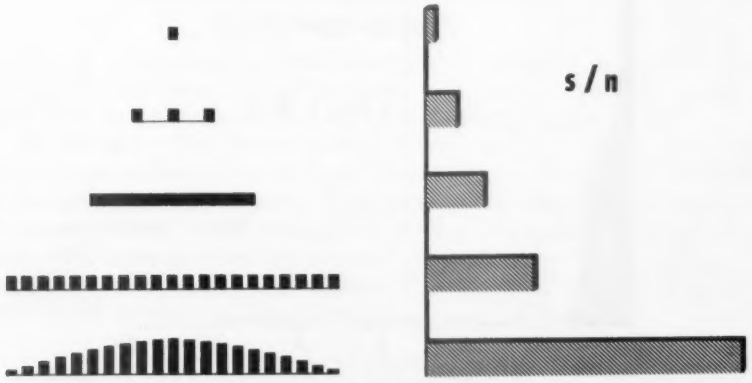

FIG. 14. A summary of the signal-to-noise ratios for the groups described in Figures 8 through 12.

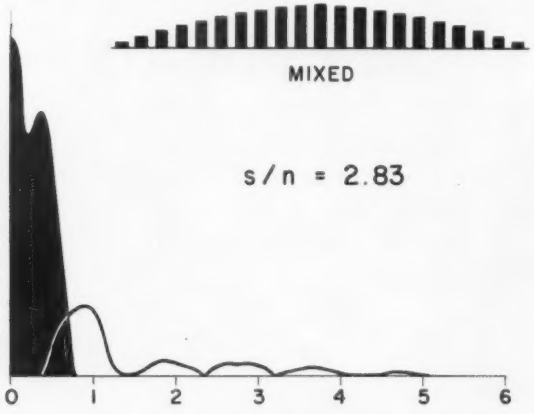

FIG. 15. The spectra of Figure 12 now modified by simple mixing (See Figure 5). The signal-to-noise ratio is 2.83.

sionally the tapered cable produced slightly better results. The immediate conclusion is that variations in seismometer planting have a considerable adverse effect on the moveout filter characteristics of the tapered array.

Non-tapered cables should, however, produce by reason of their greater *effective* ground overlap, an apparently superior record. Such superiority is produced at the cost of independence and is thus spurious since our criterion of general quality is trace-to-trace correlation. Tapered cables, on the other hand,

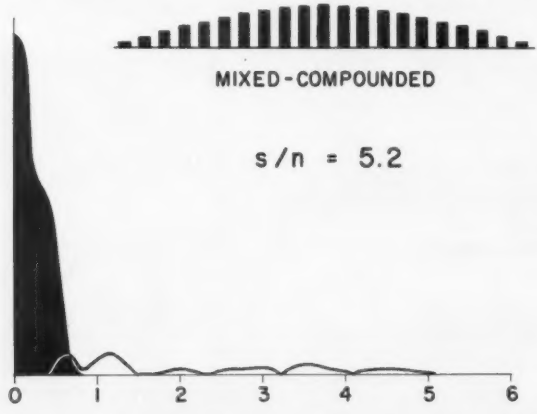

FIG. 16. The same spectra in the case of mixing and compounding used together. Effectively, in this case, four individual groups are equally mixed. The signal-to-noise ratio has reached the astonishing value of 5.2. This gain has, however, been accompanied by an appreciable loss of signal.

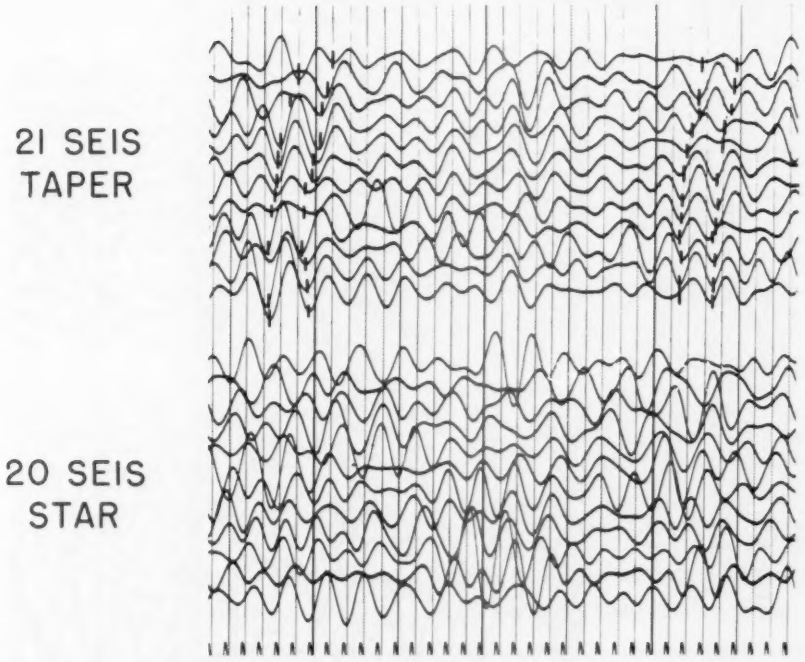

FIG. 17a. Comparison records illustrating improvement in reflection quality obtained by the use of the moveout filter. In this illustration and the succeeding comparisons (Figures 17b, c, d, e) the two spreads were superimposed with identical group centers. Areas represented are the Edwards Plateau and the Oklahoma Panhandle.

produce the same degree of overall record quality with much less *effective* overlap between groups. Thus, the fact that the record quality is the same in the two cases leads to the conclusion that the taper is effective, at least in part.

In summary, then, ground overlap between adjacent groups has a much greater effect on the independence of traces in the case of the uniform array than in the case of the tapered array. Since there is little difference between the two in apparent overall record quality, the choice of the tapered cable is indicated from considerations of information theory. Greater costs of maintenance of the electrical circuitry involved in the tapered system tend, however, to favor the non-tapered system.

VARIATIONS AND GENERALIZATIONS

Moveout filters are by no means limited to linear arrays. The same or similar techniques may be employed to design areal arrays of optimum characteristics.

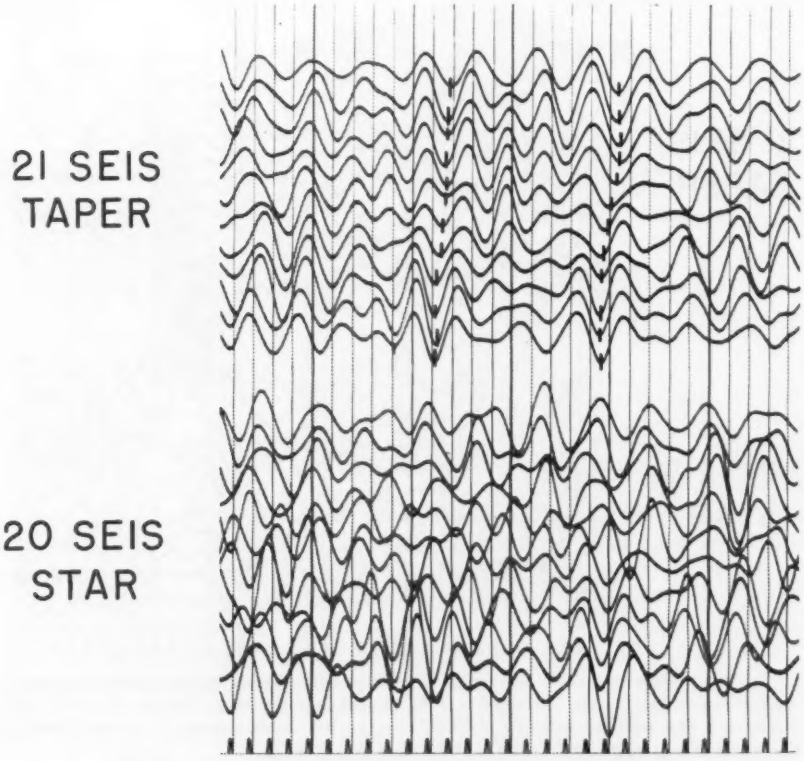

FIG. 17b. Comparison records similar to those described in Figure 17a.

Calculations and experiment have shown that the gain to be expected through the use of two-dimensional arrays is relatively small while the increased cost is quite large.

If, however, noise tests indicate that the apparent wavelengths of the signal and noise do not overlap when measured along a linear spread whose extension passes through the shotpoint, little if any gain is to be expected from a two-dimensional array as compared to a one-dimensional tapered array of the same number of seismometers. The overwhelming majority of noise tests examined by the authors fall into this category. Linear tapered arrays are, furthermore, appreciably less costly and less time consuming than most conventional multiple seismometer patterns.

It should also be pointed out that optimum arrays may be derived for groups of detectors, all of equal sensitivity or effectiveness but spaced at arbitrary posi-

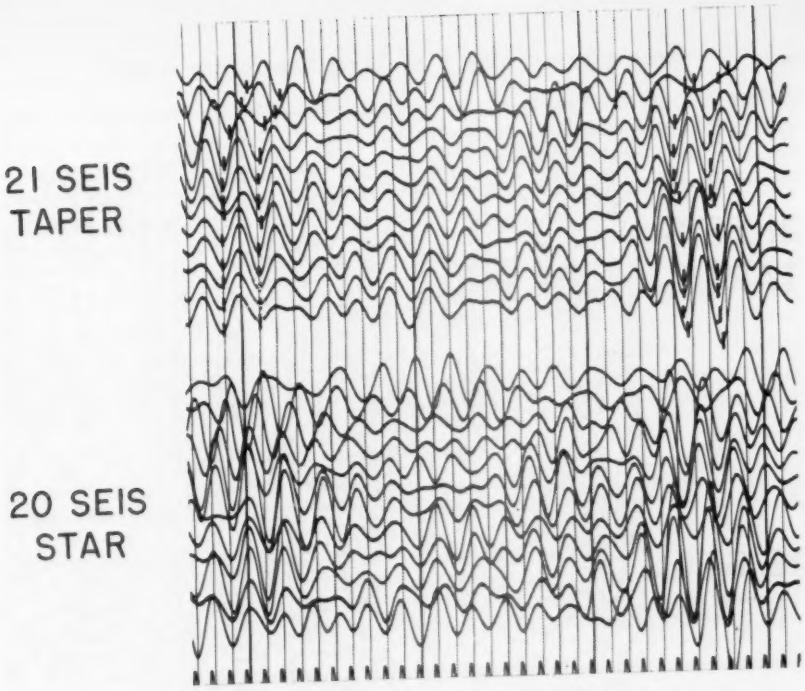

FIG. 17c. Comparison records similar to those described in Figure 17a.

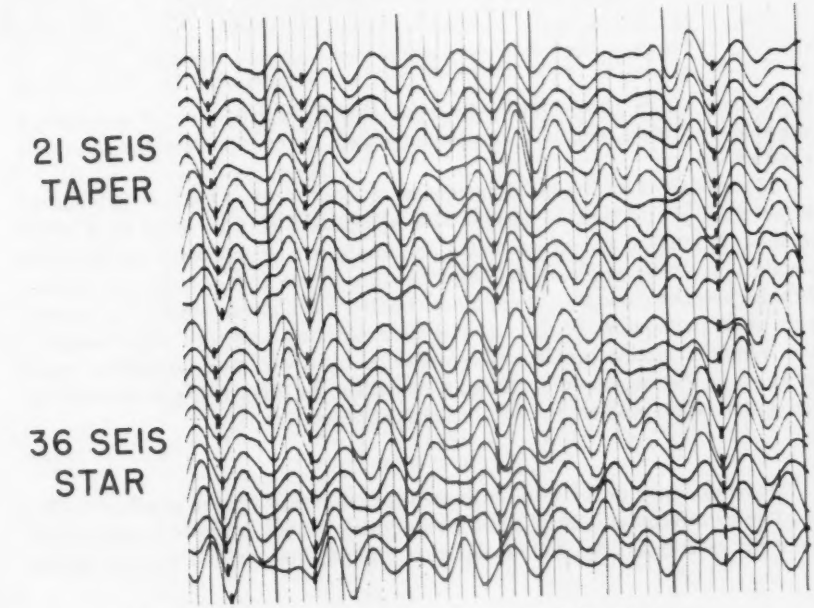

FIG. 17d. Comparison records similar to those described in Figure 17a.

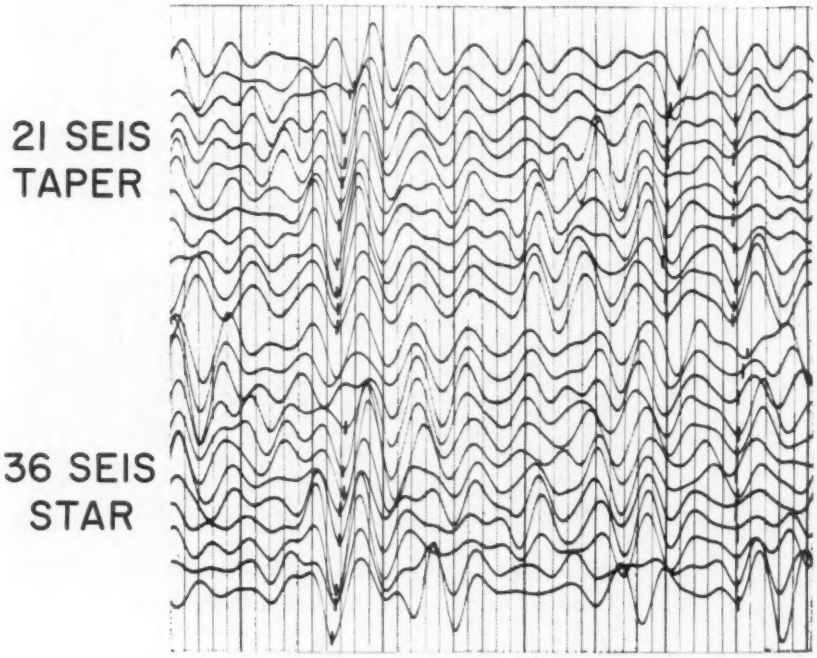

FIG. 17e. Comparison records similar to those described in Figure 17a.

tions along a line. In general it was found that for a fixed number of elements variable sensitivity permits a far closer approach to the ideal response than does variable spacing.

Application of moveout filter theory to shot patterns (or for that matter to patterns of any type of seismic wave generators) may be made by a direct method. It may be assumed that the amplitude of a seismic wave varies as the square root of the weight of explosive used (or of the energy of the generator). In this case, then, one should use a linear pattern of charges weighted in accordance with the squares of the tapering constants for detectors. Unfortunately, the seismic initiation problem is complicated by a variation for various types of waves of the amplitude-to-charge relationship. At this writing, no solution to the optimization problem for shot patterns appears near.

CONCLUSIONS

Moveout filters in the form of linear tapered groups appear to afford both a possible improvement in results and a reduction of operating costs in some of our more difficult areas. Application appears limited, however, to certain specific

areas in which high-moveout noise is prevalent and of the same frequency composition as reflections. If, in a given area, high moveout noise has a frequency spectrum substantially different from that of the reflection signals, only a small amount of moveout filtering may be necessary. In that case conventional methods should be adequate.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the many members of the Western organization who gave of their time and efforts in support of the research upon which this paper was based. In particular, the authors are indebted to Mr. Dean Walling for his constant encouragement and guidance in pursuing this project and to Miss Dorothy Stark for her preparation of the illustrations.

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GEOPHYSICS, VOL. XXIII, No. 1 (JANUARY, 1958), PP. 26–43, 12 FIGS.

TRANSIENT BEHAVIOR OF PATTERNS*

J. E. WHITE†

ABSTRACT

A simple method is described for computing the waveform to be expected from a closely-spaced pattern of shots or geophones when the individual signal is a pulse. Four strength distributions are compared, and the case of uniform strength along the pattern is discussed in detail. It is concluded that if the individual signal is a short pulse, such as a seismic reflection, then the performance of the pattern is quite comparable for the four source distributions considered.

INTRODUCTION

Arrays of sources and detectors have been treated by many authors from various viewpoints. A unifying digest of these diverse treatments of antenna arrays, directional microphones, underwater transducers, and seismic patterns would be worthwhile, but such a survey will not be attempted here. The purpose of this discussion is to extend existing theory in two respects, both intended to make it more easily applied to seismic prospecting. Quantitative measurements by a research seismic crew have shown that this type of theory does apply to seismic signals under practical field conditions. First, the performance of a pattern is described in terms of transient waveforms rather than in terms of amplitudes of sine-wave components making up the transients. Secondly, the output waveforms are plotted as a function of delay-time across the pattern, rather than as directivity diagrams. The results are more easily applied to waveforms observed in seismic prospecting, and refractions, shear waves, or events of unknown origin can be handled equally well without the question ever arising as to where they belong on a directivity plot.

STATEMENT OF THE PROBLEM

Some Special Cases

In Figure 1, detectors down a borehole are assumed to receive first a reflection being transmitted by the formation in which the borehole is drilled, followed by a noise wave with a different step-out, borne by fluid in the hole. In (a), the reflection is shown to have a total delay across the pattern of Δt_{m_1}, which when divided into the pattern length L gives the speed of compressional waves in the formation. Similarly, Δt_{m_2} yields the speed of borehole waves. The important quantity is the delay time Δt_m. We assume that signals from the detectors can

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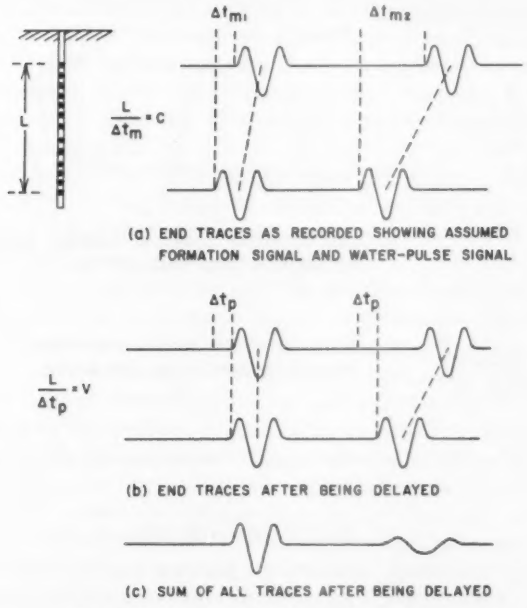
Δt_{m1}
Δt_{m2}
L
$\frac{L}{\Delta t_m} = C$
(a) END TRACES AS RECORDED SHOWING ASSUMED FORMATION SIGNAL AND WATER-PULSE SIGNAL
Δt_p
Δt_p
$\frac{L}{\Delta t_p} = V$
(b) END TRACES AFTER BEING DELAYED
(c) SUM OF ALL TRACES AFTER BEING DELAYED

FIG. 1. Pattern of vertically-spaced detectors.

be shifted so that the relative delay between the ends is Δt_p, which can be adjusted to counteract any amount of delay Δt_m due to the medium. It is apparent that it is the difference between Δt_m and Δt_p which controls the final sum, such as is shown in (c). It is useful to define a pattern velocity $V = L/\Delta t_p$.

The same terminology is applied to a surface line of geophones, as shown in Figure 2. Since the geophone outputs are simply added without relative delay, the pattern velocity is infinite and the "step-out" Δt_m controls the sum waveform.

The expressions presented here apply to the situation shown in Figure 3, although it might not at first look like a pattern of detectors. Playback heads are equally spaced around a drum which carries the tape past the heads at a speed C. The delay Δt_m is the same for all pulses. The two pulses shown have the same basic shape, but one lasts twice as long as the other. The sum trace shows that the two pulses fare differently, bringing out the obvious point that the output of a linear pattern depends on the duration of the pulse as well as the delay across the pattern.

Definitions of Terms

A pattern is assumed to contain so many elements that it can be considered

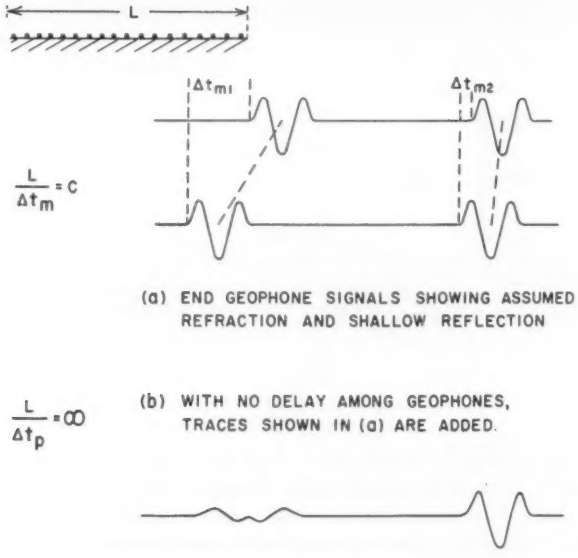
L
Δtm1
Δtm2
L/Δtm = c
(a) END GEOPHONE SIGNALS SHOWING ASSUMED REFRACTION AND SHALLOW REFLECTION
L/Δtp = ∞
(b) WITH NO DELAY AMONG GEOPHONES, TRACES SHOWN IN (a) ARE ADDED.
(c) SUM OF GEOPHONE SIGNALS

FIG. 2. Linear pattern of geophones on surface.

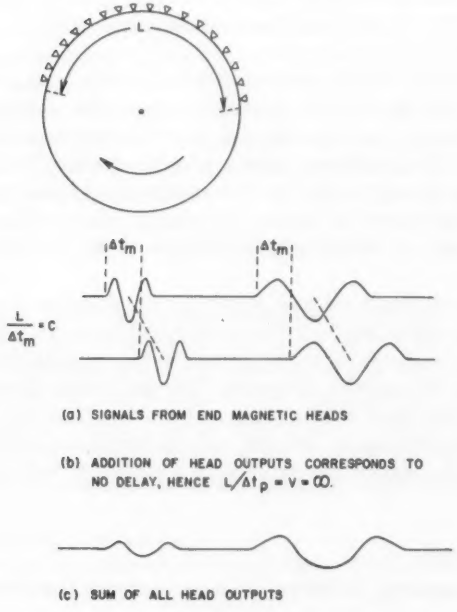
L
Δtm
Δtm
L/Δtm = c
(a) SIGNALS FROM END MAGNETIC HEADS
(b) ADDITION OF HEAD OUTPUTS CORRESPONDS TO NO DELAY, HENCE L/Δtp = V = ∞.
(c) SUM OF ALL HEAD OUTPUTS

FIG. 3. Heads spaced along a magnetic tape trace.

continuous. It is characterized by a strength per unit length $A(x/L)$. The contribution to the final signal due to a short length dx is proportional to $A(x/L)dx$. For an array of lumped elements, $A(x/L)$ would be equivalent to the signal due to one lumped element divided by the spacing between elements. A second characteristic of a pattern is a velocity V, as discussed above, which with a length L results in a pattern delay Δt_p.

There will be a delay across the pattern Δt_m which is due to the medium to which the pattern is coupled. It can be thought of as being due to a velocity $C = L/\Delta t_m$, which will be different for various types of waves and which will vary with angle of arrival for any one type of wave.

Any waveform is a plot of some ordinate as a function of time. We shall normalize our plots so that a change in ordinate scale will not be considered to produce a new waveform. A simple way is to divide the ordinates by the largest ordinate, giving a non-dimensional waveform with a peak value of one regardless of the size of the original numbers. The time axis can similarly be expressed in non-dimensional form by dividing all time values by some "apparent period" T of the waveform. Then all waveforms which have the same shape except for different durations in actual time will become identical when plotted in non-dimensional form. The choice of a characteristic time or "apparent period" for a given waveform is somewhat arbitrary, although the term is commonly applied to seismic transients and there is general agreement as to how this choice should be made. Apparent periods are shown on the various waveforms treated.

Transient Response by Three Methods

Before taking up the behavior of distributed sources and detectors, the behavior of a simple circuit element will be discussed as an illustration of the viewpoint.

One "fundamental" description of a condenser is the equation $e(t) = \int i(t)dt/C$ relating the voltage $e(t)$ across the condenser to the current $i(t)$ flowing in the condenser. Let us assume that the current is some known function of time, which then serves as an input, and the voltage is some function of time to be determined, which is the output. From the equation, it is seen that any graphical or other method of integrating the current waveform will yield the voltage waveform. Hence, this is one computational method of solving the problem.

A second "fundamental" description of the circuit element is its impulse response. The impulse response is the output waveform when the input consists of an instantaneous spike. The spike is a definite function known as the unit impulse $u_1(t)$, which is infinitely large in magnitude when $t = 0$ but which is so short in duration that its time integral has a finite value, defined to be unity. This integral is the unit step-function $u(t)$, which is zero until $t = 0$ and has unit magnitude thereafter. This is stated by $\int u_1(t)dt = u(t)$. In Figure 4, the input current is shown to be a unit impulse and the resulting voltage is "the impulse response of the system." As discussed later under the heading "Impulse Response of

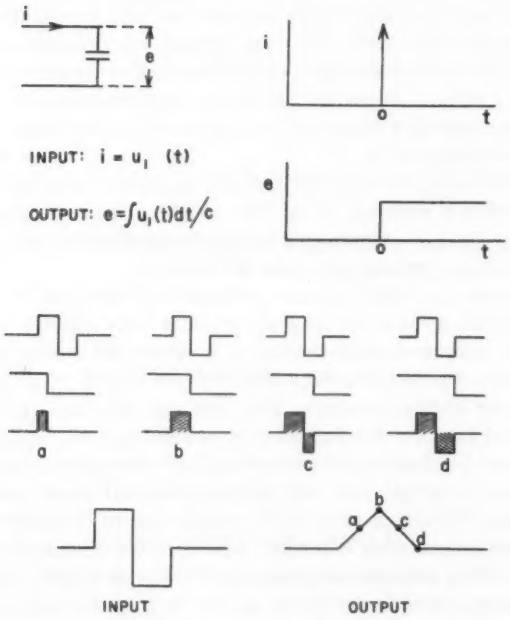

FIG. 4. Impulse response of a condenser.

Patterns," the output waveform due to any assumed input waveform can be computed by convolving the input with the impulse response. Four points obtained by convolution are indicated by *a*, *b*, *c*, and *d* in Figure 4. The assumed waveform is shown as the top line in each case. The impulse response plotted on a reversed time axis is shown on the second line, its position relative to the input being different in each case. The product is shown on the third line. The quantity desired is the integral of the product, or the area under the curve. Points *a*, *b*, *c*, and *d* on the output curve are proportional to the respective areas shown. This illustrates the computational steps involved in using the impulse response of a system to determine its response to an arbitrary input transient.

A third "fundamental" description of the circuit element is its steady-state response. This is determined by assuming that the input is a sinusoidal function of time, $i(t) = I \sin \omega t$, in which case the output is also a sinusoidal function of time with an amplitude and a phase angle, $e(t) = E \sin (\omega t + \theta)$. The steady-state response of the system is the ratio E/I and the phase angle θ specified as functions of frequency. These are shown in Figure 5. They, of course, simply describe the electrical impedance of a condenser. This description can be applied to any desired input waveform by use of the Fourier integral theorem. By Fourier analysis, any input transient can be specified by its frequency content, that is,

by an amplitude and phase angle as functions of frequency. Multiplication of the amplitude function by (E/I) and addition of θ to the phase function gives two new functions of frequency which are the frequency representation of the output waveform. The output function of time can then be computed, a process which is commonly known as Fourier synthesis. All of the time and frequency representations of one possible input waveform are shown qualitatively in Figure 5. These steps constitute a fair-sized computational program, even with suitable high-speed computing facilities.

PATTERN OUTPUT AS A SUM OF TRANSIENT WAVEFORMS

The purpose of this section is to derive expressions for the waveforms put out by a few patterns in terms of integrals of the waveform due to an element of

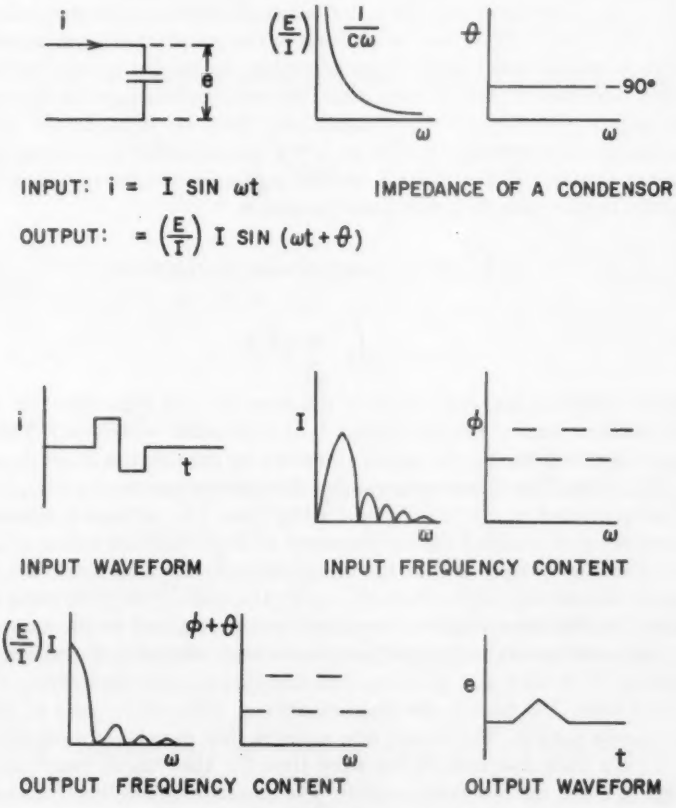

FIG. 5. Sine-wave behavior of a condenser.

the pattern. This type of equation states the behavior of a pattern in a form particularly well adapted to short transients. In the simpler cases, output waveforms can be obtained qualitatively by simply sketching the appropriate integrated pulses and combining them. In any case, the equation offers a straightforward means of computing output waveforms for any assumed elementary transient.

General Expression

Let us assume that a source lies on the x-axis between O and L. Let us take the signal generated at the origin as a reference for counting time, that is, $A(o)f(t)dx$ expresses the strength and waveform due to the element dx near $x=o$. This contribution is made at the receiver after some travel time T_0, which is expressed by $A(o)f(t-T_0)dx$. The source is initiated at $x=o$ and proceeds at a velocity V in the direction of positive x, and hence the signal at the source for any value of x is $f(t-x/V)A(x/L)dx$. In addition to the travel time T_0, it is assumed that there is an additional delay which is greater, the further a point lies in the negative x direction. At the receiver, then, the contribution from an element dx centered at x is $f(t-T_0-x/V+x/C)A(x/L)dx$. The total signal at the receiver is the integral of this quantity from O to L. We can normalize by dividing by the total source strength $\int_0^L A(x/L)dx$. A general expression for the transient waveform at the receiver due to a distributed source is

$$F(t) = \frac{\int_0^L f(t - T_0 + x/C - x/V)\,A(x/L)dx}{\int_0^L A(x/L)dx}. \qquad (1)$$

Slightly different language leads to the same general expression for a distributed receiver located between O and L. If a transient waveform $f(t)$ reaches the origin after a delay T_0, the signal generated by the element dx at the origin is $f(t-T_0)A(o)dx$. The disturbance reaches the positive values of x first, so that the signal generated at x is $f(t-T_0+x/C)A(x/L)dx$. The receiver is assumed to have a property of delaying signals generated at larger positive values of x with respect to smaller values, so that the contribution to the final signal due to an element dx located at x is $f(t-T_0+x/C-x/V)A(x/L)dx$. This is the same as the expression for the source and is integrated and normalized in the same way. Hence, the same general expression applies to both sources and receivers. For convenience of writing and plotting, two non-dimensional parameters will be introduced here. The first is the measurement of distance in units of pattern length, namely $y=x/L$. The second is to measure time in units of some arbitrary period T. We shall also remove the fixed time T_0, the "travel time" between the origin of x and the observation point. The non-dimensional time parameter τ

is defined as $\tau=(t-T_0)/T$. We shall also define the differential delay across the pattern in the same non-dimensional scale, namely $\Delta\tau=(\Delta t_p-\Delta t_m)/T$. In dimensionless form, equation (1) is:

$$F(\tau) = \frac{\int_0^1 f(\tau - y\Delta\tau)\,A(y)dy}{\int_0^1 A(y)dy}. \tag{2}$$

In these terms, the total source strength C is:

$$C = \int_0^L A(x/L)dx = L\int_0^1 A(y)dy. \tag{3}$$

Uniform Strength Distribution

If the source or receiver strength is constant along its length, integration of equation (2) gives:

$$F_0(\tau) = \frac{\int_0^\tau f(\tau)d\tau - \int_0^\tau f(\tau - \Delta\tau)\cdot d\tau}{\Delta\tau}. \tag{4}$$

It should be noted that if the constant source strength has the value A_0, then the total strength of the pattern is

$$C_0 = \int_0^L A_0 dx = A_0 L. \tag{5}$$

Triangular Strength Distribution

A strength distribution which is zero at the ends and builds up linearly to a maximum value A_1 at the middle is expressed by these conditions:

$$\begin{aligned} A(y) &= 2yA_1 \qquad \text{for} \quad 0 < y < 1/2 \\ A(y) &= 2(1-y)A_1 \quad \text{for} \quad 1/2 < y < 1. \end{aligned} \tag{6}$$

These conditions are put into equation (1), which is then integrated in two pieces. The resulting dimensionless waveform due to a triangular distribution is:

$$F_1(\tau) = \frac{\int_0^\tau\int_0^{\tau_1} f(\tau)d\tau d\tau_1 - 2\int_0^\tau\int_0^{\tau_1} f(\tau-\Delta\tau/2)d\tau d\tau_1 + \int_0^\tau\int_0^{\tau_1} f(\tau-\Delta\tau)d\tau d\tau_1}{(\Delta\tau/2)^2}. \tag{7}$$

The total source strength of the pattern is:

$$C_1 = L\int_0^{1/2} 2yA_1dy + L\int_{1/2}^{1} 2(1-y)A_1dy = A_1L/2. \tag{8}$$

"House-Top" Strength Distribution

It is apparent that the outputs of two patterns acting simultaneously can simply be added. The dimensionless waveform due to the sum of a uniform distribution and a triangular distribution is:

$$F_2(\tau) = \frac{C_0F_0(\tau) + C_1F_1(\tau)}{C_0 + C_1}. \tag{9}$$

Some Other Symmetrical Distributions

Jones (1945) published the steady-state responses of a whole family of source distributions, all of which have a maximum value in the middle of the pattern and drop off smoothly to zero at the ends. We give here the transient expression for the case

$$A(y) = [1 - 4(y - \tfrac{1}{2})^2]A_3. \tag{10}$$

Equation (1) has been integrated for this case, giving for the dimensionless waveform:

$$F_3(\tau) = \frac{3}{2}\left[\frac{\int_0^{\tau}\int_0^{\tau_1} f(\tau)d\tau d\tau_1 + \int_0^{\tau}\int_0^{\tau_1} f(\tau-\Delta\tau)d\tau d\tau_1}{(\Delta\tau/2)^2} - \frac{\int_0^{\tau}\int_0^{\tau_1}\int_0^{\tau_2} f(\tau)d\tau d\tau_1 d\tau_2 - \int_0^{\tau}\int_0^{\tau_1}\int_0^{\tau_2} f(\tau)d\tau d\tau_1 d\tau_2}{(\Delta\tau/2)^3}\right]. \tag{11}$$

The total source strength of the pattern is:

$$C_3 = L\int_0^1 [1 - 4(y - \tfrac{1}{2})^2]A_3dy = 2A_3L/3. \tag{12}$$

Jones also discussed the distributions proportional to $[1-4(y-1/2)^2]$ raised to the second, third, and fourth power, as well as other symmetrical distributions. For all these cases, the output waveform can be expressed as a sum of integrals of the basic waveform, but the number of terms would be large, and hence the equations would be less useful for computing output waveforms or for visualizing the performance qualitatively.

IMPULSE RESPONSE OF PATTERNS

Some Remarks About Impulse Responses

It is well known that the complete performance of a linear system can be expressed by its impulse response. A linear system is one in which an input function of time and an output function of time are related through a linear differential equation. The impulse response is the output waveform $I(t)$ resulting when the input is a unit impulse, $u_1(t)$. The unit impulse is zero for all values of t except $t=0$, at which point it is infinite in such a way that $\int u_1(t)dt=1$. The impulse response may be of interest in itself, but one of its important characteristics is that it provides a means of computing the output waveform $F(t)$ due to any input waveform $f(t)$ through the convolution integral

$$F(t) = \int_0^t I(t-z)f(z)dz.$$

Application to the General Expression

If we assume that the waveform due to an elementary length of pattern is $u_1(t)$, then equation (1) becomes

$$I(t) = \frac{\int_0^L u_1(t - T_0 + x/C - x/V)\,A(x/L)dx}{\int_0^L A(x/L)dx}. \tag{13}$$

Using the relation $d\tau=(\Delta\tau)dy$, equation (13) can be written

$$I(\tau) = \frac{\int_0^{\Delta\tau} u_1(\tau - y\Delta\tau)\,A(y)d\tau}{\left[\int_0^1 A(y)dy\right]\Delta\tau}. \tag{14}$$

The effect of integration of the numerator is to put in $A(y)$ those values of y for which $(\tau-y\Delta\tau)=0$. This gives a general expression for the impulse response of a pattern with any strength distribution $A(y)$:

$$I(\tau) = \frac{A(\tau/\Delta\tau)/\Delta\tau}{\int_0^1 A(y)dy}. \tag{15}$$

Uniform Strength Distribution

For this case, $I_0(\tau)$ has the constant value $1/\Delta\tau$ from $\tau=0$ to $\tau=\Delta\tau$ and is zero elsewhere:

If $\Delta\tau$ is positive

$$I_0(\tau) = 1/\Delta\tau, \qquad 0 < \tau < \Delta\tau. \tag{16}$$

If $\Delta\tau$ is negative

$$I_0(\tau) = -1/\Delta\tau, \qquad \Delta\tau < \tau < 0.$$

Triangular Strength Distribution

Using equations (6) and (8), the impulse response for a triangular strength distribution from equation (15) is:

When $\Delta\tau$ is positive:

$$\begin{aligned} I_1(\tau) &= 2(\tau/\Delta\tau)/\Delta\tau, & 0 < \tau < \Delta\tau/2 \\ I_1(\tau) &= 2(1 - \tau/\Delta\tau)/\Delta\tau, & \Delta\tau/2 < \tau < \Delta\tau. \end{aligned} \tag{17}$$

When $\Delta\tau$ is negative:

$$\begin{aligned} I_1(\tau) &= -2(\tau/\Delta\tau)/\Delta\tau, & \Delta\tau/2 < \tau < 0 \\ I_1(\tau) &= -2(1 - \tau/\Delta\tau)/\Delta\tau, & \Delta\tau < \tau < \Delta\tau/2. \end{aligned}$$

"House-Top" Strength Distribution

The combined impulse response for more than one distribution acting simultaneously is again the sum of the individual responses properly weighted. Hence the impulse response due to a combination of a uniform distribution and a triangular distribution is:

$$I_2(\tau) = [C_0 I_0(\tau) + C_1 I_1(\tau)]/(C_0 + C_1). \tag{18}$$

Other Strength Distributions

For the distribution described by equation (10), the impulse response from equation (15) is:

When $\Delta\tau$ is positive:

$$I_3(\tau) = 3[1 - 4(\tau/\Delta\tau - \tfrac{1}{2})^2]/2\Delta\tau, \qquad 0 < \tau < \Delta\tau.$$

When $\Delta\tau$ is negative:

$$I_3(\tau) = -3[1 - 4(\tau/\Delta\tau - \tfrac{1}{2})^2]/2\Delta\tau, \qquad \Delta\tau < \tau < 0. \tag{19}$$

It is apparent from the above examples that the impulse response of any pattern is the same function of $\tau/\Delta\tau$ that the source distribution is of y, normalized in such a way that $\int I(\tau)d\tau = 1$. Hence, for any strength distribution whatever, the impulse response can be written down immediately and normalized very simply.

STEADY-STATE REPRESENTATION

Because the steady-state behavior of patterns has been so thoroughly covered in publications, the sine-wave responses of these strength distributions will not

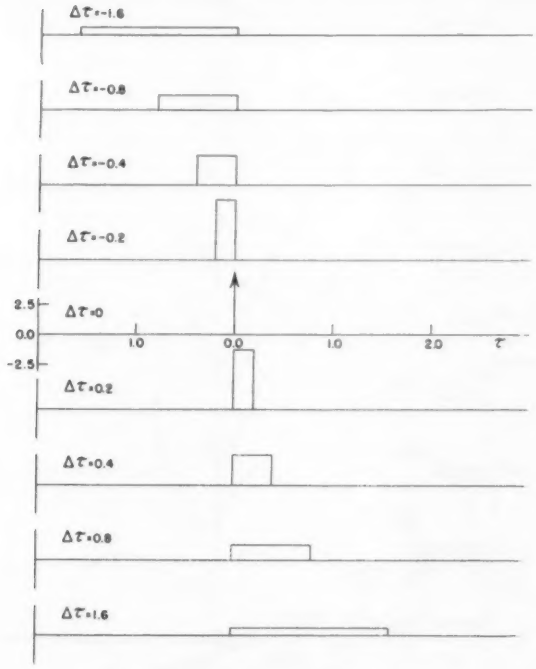

FIG. 6. Uniform distribution: Impulse response.

be given here. They are the Fourier transforms of the respective impulse responses.

DISCUSSION OF RESULTS

Uniform Strength Distribution

Impulse response curves for this type of pattern are plotted in Figure 6 for selected values of $\Delta\tau$. For $\Delta\tau = 0$, the curve is an infinite spike, or unit impulse. As $\Delta\tau$ increases, the impulse response continues to be a replica of the strength distribution with the height and width of the pulse varying so that the area is always unity.

The effect of this pattern on a simple waveform is shown in Figure 7. The waveform for each value of $\Delta\tau$ can be obtained by convolving the simple waveform with the appropriate impulse response or by use of equation (4).

Several interesting points are set forth in Figure 7. An obvious one is the fact that as the delay $\Delta\tau$ increases, the amplitude decreases and the pulse spreads out. If $\Delta\tau$ is larger than the duration of the original pulse, the output consists of

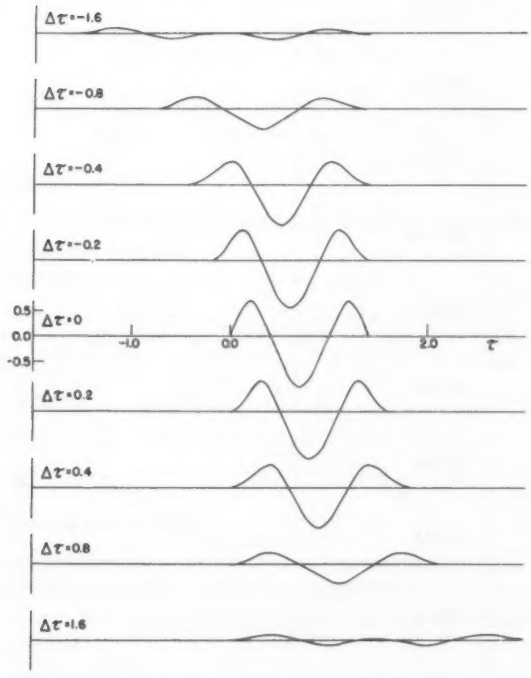

FIG. 7. Uniform distribution: Computed waveforms.

two separate pulses with a dead space between them. For the waveform shown, output amplitudes decrease smoothly with no rebound points. This shows that for a short pulse, which necessarily contains energy in a fairly wide frequency band, there is no critical length of pattern which will "tune in" and really eliminate the signal. A second point is the shift in arrival time of the center of the pulse. In a way, this shift occurs because we have taken the reference time to be the time when the beginning of the basic waveform occurs at one end of the pattern. This can best be discussed with a particular physical pattern in mind, for which purpose we shall choose a bag of powder in a vertical hole being fired from the top. If formation speed is greater than the speed of burning of the powder, the first signal to be detected will always be due to the part of the charge which fires first. The effect of the rest of the string is felt later, and the delay $\Delta\tau$ is defined to be positive in this case. Since the moment of detonation is the time reference, the onset of the signal will be the same for all positive values of $\Delta\tau$. If, on the other hand, the powder velocity is higher than formation speed, the signal from the bottom of the string may be received first, which would be called a negative $\Delta\tau$. In this case, the onset of the signal is earlier by an amount which

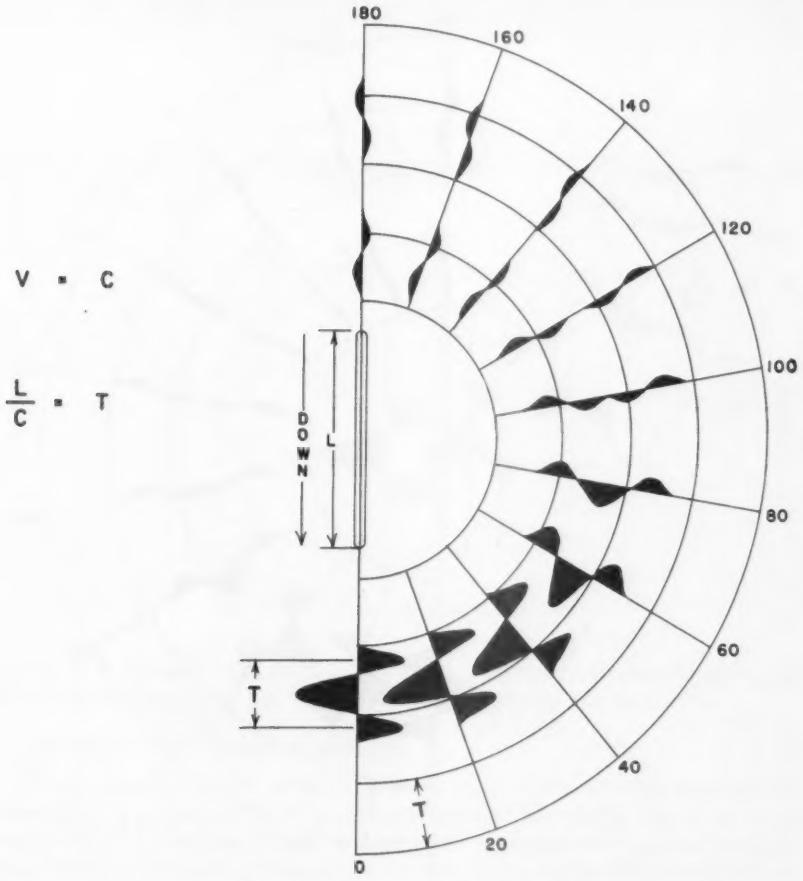

FIG. 8. Waveforms due to matched powder string.

depends on $\Delta\tau$. Note that the center of the waveform shifts as $\Delta\tau$ varies. These can be looked at as reflection waveforms due to powder strings of different burning speeds, always using a high-gain uphole phone as a time correction. If the powder burns faster than formation speed, the event comes in early; if slower, it comes in late. The waveform is also different, depending on the degree of mismatch.

For a given powder speed, the waveform will change in a similar way with direction of radiation from the string. Figure 8 shows how the size and shape of the radiated signal varies with angle when powder and formation speeds are the

$$V = \frac{C}{1.2}$$

$$\frac{L}{C} = T$$

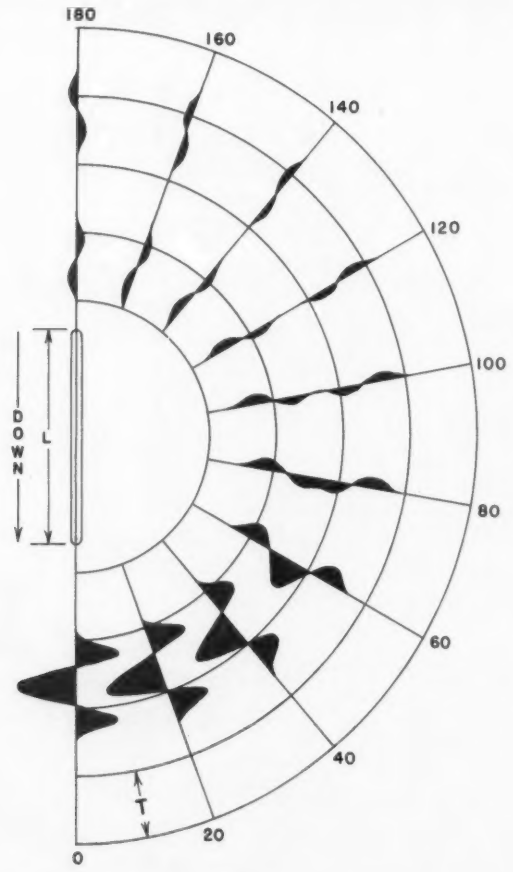

FIG. 9. Waveforms due to over-delayed powder string.

same. Arrivals are adjusted so the center of the pulse always comes at the same time, rather than relative to an uphole phone break. The same type of plot is shown in Figure 9 for a powder string which is over-delayed so as to show "super-directivity." It is not strikingly different from the case of matched speeds, although peak-to-peak amplitude does decrease somewhat faster with angle near the downward direction.

The same expressions apply to detectors. Figure 10 shows the output of a line of closely-spaced geophones electrically in parallel and lying on a uniform

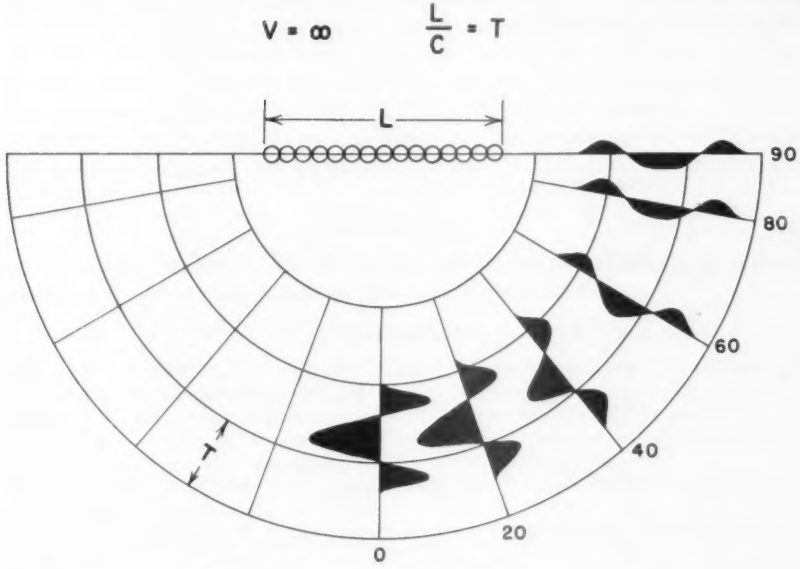

FIG. 10. Waveforms due to line of geophones.

earth. It is apparent that reflections arriving at large angles may be given an abnormal low-frequency appearance when large patterns are used.

Comparison of Four Strength Distributions

Many treatments show in terms of steady-state expressions that tapering the strength of a pattern along its length may provide advantages over a uniform distribution of strength. Figure 11 compares the performance of four strength distributions when acting on a simple wavelet. These curves were computed on the ElectroData computer by the process of convolving equations 16, 17, 18, and 19 respectively with the simple wavelet which is shown in each case as the waveform when there is no time shift. It was anticipated that for large values of $\Delta\tau$, either of the last two cases would result in smaller residual signal than was obtained with the uniform distribution. This turns out to be true by a small factor, but it appears that for small values of $\Delta\tau$, the details of the strength distribution have very little effect on the resulting waveform.

Comparison of Two Lumped-Element Patterns

Figure 12 gives an added example of the transient behavior of a strength distribution for which the sine-wave performance has been published. In their Fig-

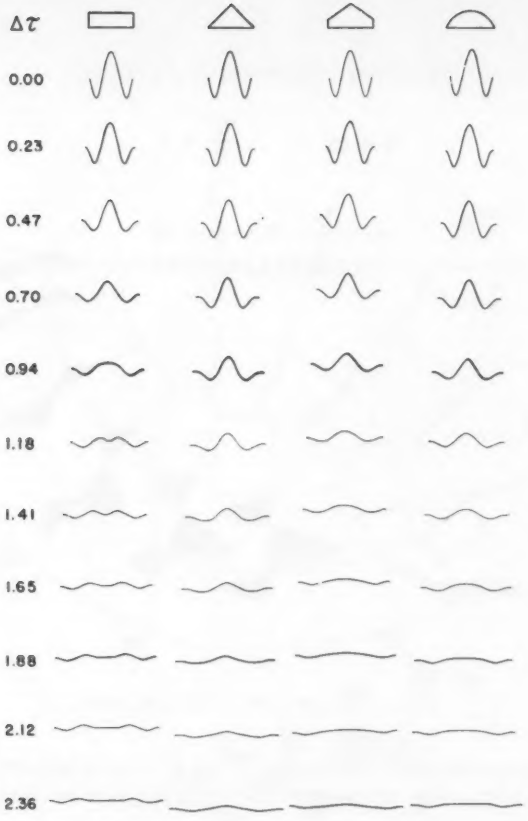

FIG. 11. Waveforms for four distributions.

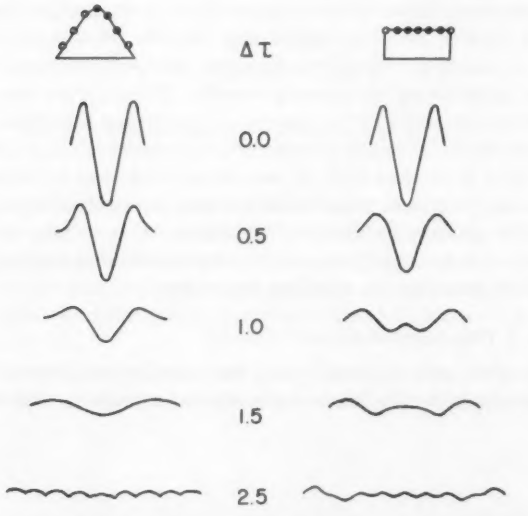

FIG. 12. Comparison of two strength distributions for seven-element array.

ure 6, Parr and Mayne (1955) show the increased rejection within a frequency band which can be achieved by proper gradation of effectiveness of seven lumped elements, as compared with seven uniformly sensitive elements with the same spacing. Since the increased rejection is accompanied by decreased band width, it is not easy to visualize the relative effects of these two patterns on a short wavelet. The gradation of strength corresponding to Choice 1 in Parr and Maynes Figure 6 was computed, and the resulting comparison of waveforms is presented in Figure 12.

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GEOPHYSICS, VOL. XXIII, NO. 1 (JANUARY, 1958), PP. 44–57, 12 FIGS.

A REVIEW OF METHODS OF FILTERING SEISMIC DATA*

MARK K. SMITH†

ABSTRACT

Filtering in its general sense represents an important phase of data processing. In recent years such new methods as delay line filtering and digital filtering as well as conventional seismic filtering have been described in the literature. The purpose of this paper is to clarify the relationship between these methods of filtering and to compare design criteria such as cross-correlation filtering and zero-phase filtering. Synthetic records as well as field records are used to illustrate the effects of the various filtering techniques.

INTRODUCTION

Conventional seismic filters (of the band pass type) are usually contemplated in terms of their cut off points and rejection rates or slopes. Such general terms as a 21-cycle-per-second sharp or double section low cut and a 75-cycle-per-second soft or single section high cut, commonly suffice to describe a seismic filter setting and imply its application (i.e., to reject low frequency ground roll and high frequency wind noise without materially disturbing the reflection characteristics). In recent years, unconventional filtering methods have been applied to seismic data such as digital filtering (Wadsworth et al., 1953; M.I.T. Geophysical Analysis Group Reports, 1953, 1954, 1955), and delay line filtering (Jones et al., 1955), as well as flexible electrical filtering. When used with magnetically stored data and high speed data processing equipment, these general filtering techniques are attractive because of their great flexibility in representing a wide variety of filter characteristics. Since general filter characteristics and their applications cannot be adequately described in terms of cut off points and slopes, however, plus the fact that, mechanically, digital filtering and delay line filtering appear to differ from electrical filtering, some confusion may exist as to the relationship between these filtering methods. The purpose of this paper is to review briefly conventional filtering, delay line filtering, and digital filtering, and to attempt to illustrate the similarity of the three methods without recourse to mathematics. In addition, such filter design criteria as cross-correlation filtering (Jones and Morrison, 1954) and zero-phase filtering will be similarly illustrated and related. These filtering techniques represent data processing tools, and it is not the purpose of this paper to justify or promote one above the other.

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FILTER RESPONSE

The characteristics of a seismic filter are commonly described in terms of amplitude and phase response. Although the amplitude response (relative attenuation of frequencies passing through the filter) is often considered to be the dominating characteristic of a seismic filter, the phase response can have a profound effect on the character of the output signal. Both response curves are required to describe a filter adequately. Figure 1 shows response curves for a typical seismic amplifier and filter.

Other methods of describing the characteristics of a filter are equally well known. Among these is the impulse response or the response of the filter to a

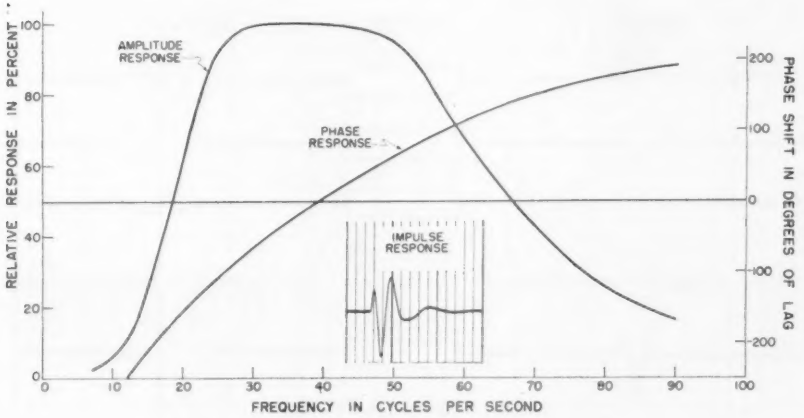

FIG. 1. Response curves for a typical seismic amplifier and filter.

spike or sharp pulse. Figure 1 also shows the impulse response of the same amplifier and filter. For practical purposes, either the impulse response or the amplitude and phase response uniquely describe the filter action; in fact, one can be mathematically derived from the other. The impulse response will be particularly useful in relating the various methods of filtering to be reviewed.

One interpretation of the significance of the impulse response is shown in Figure 2. The top three traces show input impulses of various magnitudes, polarities, and initiation times; and the resulting outputs or impulse responses with corresponding magnitudes, polarities, and delays. For example, the input to trace 2 is inverted, of greater magnitude, and delayed by six milliseconds with respect to trace 1. The output trace 2 is similarly inverted, of greater magnitude, and delayed by six milliseconds with respect to the output trace 1. Trace 4 shows the input traces added to simulate the dotted wavelet, and the output traces added to give the output of the filter when the wavelet is applied to the input.

In fact, the summed output was actually obtained by passing the input wavelet through a filter.

CONVENTIONAL, DELAY LINE, AND DIGITAL FILTERING

Figure 3 will help to illustrate delay line filtering and digital filtering. In magnetic delay line filtering (Jones et al., 1955), the input is applied to the recording head of a magnetic delay drum or delay line, and the output is formed by (1) sampling the input data at delayed points around the drum by means of pickup heads, (2) weighting the output of the individual pickup heads (including polarity reversing), and (3) summing or mixing the weighted head outputs. This operation is schematically represented in the second line of Figure 3. The input signal

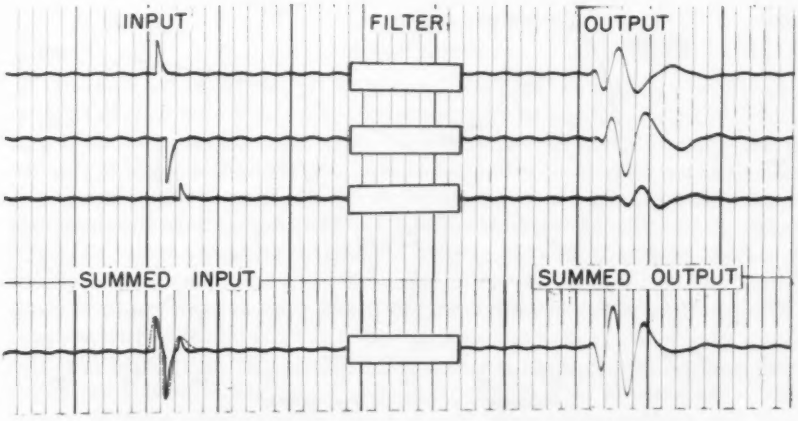

FIG. 2. Illustration of the significance of the impulse response.

is applied to the delay drum by the square recording head. The round pickup heads sample the recorded signal at progressively increasing delays, and the potentiometers symbolize the weighting of the head outputs where the weighting factors are the constants a_1, a_2, a_3, etc. The weighted head outputs are then added together to form the output of the delay line filter. The weighting factors a_1, a_2, a_3, etc., and the corresponding pickup head locations determine the filter characteristics of the delay line filter. In particular, the values of the weighting factors and the time locations of their corresponding pickup heads give the impulse response directly.

Conceptually, digital filtering is very similar to delay line filtering. First, however, the input signal must be digitized (i.e., trace amplitudes read at uniform time intervals and converted to numbers). Then, just as in delay line filtering, the input data is sampled and weighted (multiplied by a constant) at progressively delayed points, and the weighted samples are added to form the digital

output. Line 3 of Figure 3 schematically illustrates digital filtering. The digitized input signal is sampled at the time delays represented by the arrows, multiplied by the weighting factors a_1, a_2, a_3, etc., and the weighted samples are added to form the output.

The similarity of conventional, delay line, and digital filtering may now be seen by applying an impulse or sharp spike to the input of the three filters represented in Figure 3. The output of the conventional filter (trace 1) will be the

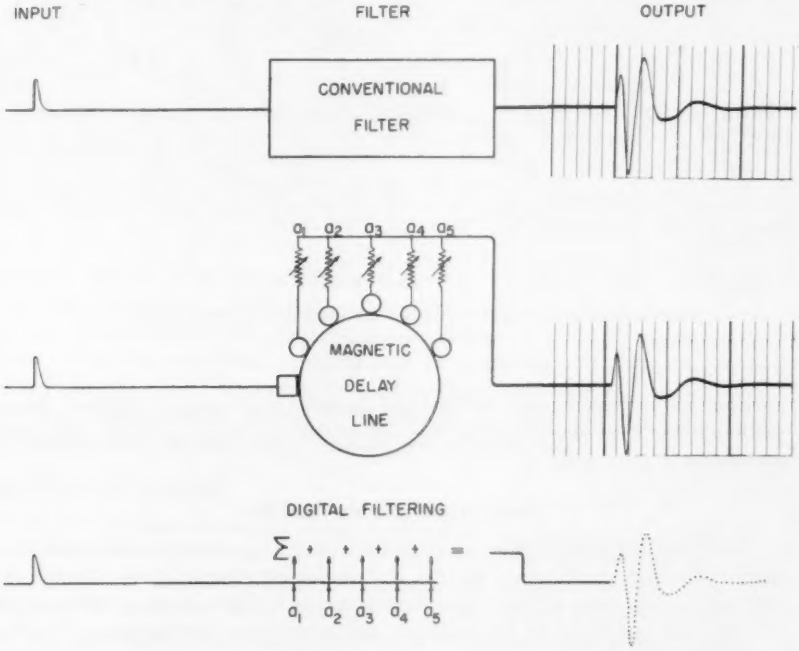

FIG. 3. Schematic representation of delay line filtering and digital filtering.

impulse response of the filter as previously described. In the case of delay line filtering (trace 2) and digital filtering (trace 3), the outputs will likewise be the impulse responses of the filters. In fact, if we visualize the input impulse recorded on the delay line filter at the recording head, then as the impulse moves around the drum, the location and weighting factor of the pickup heads will directly generate the impulse response of the delay line filter. Thus, since the impulse response uniquely determines the characteristics of a filter, the delay line filter and digital filter may be made to simulate a specific conventional filter by adjusting the weighting factors and pickup head locations or sampling points to simulate the impulse response of the conventional filter. See Figure 3. Figure 4 shows

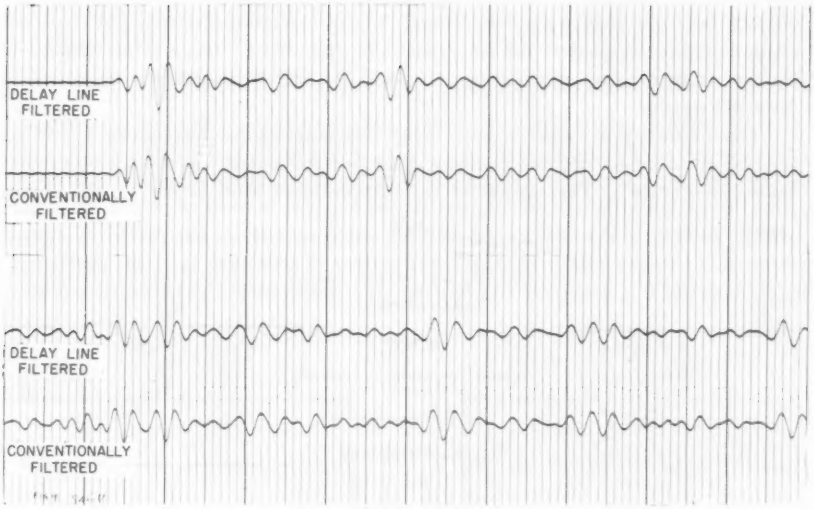

FIG. 4. Seismic trace filtered by delay line simulation of conventional filter and by conventional filter.

a seismic trace conventionally filtered and the same trace delay line filtered, where the delay line filter simulates the response of the conventional filter. The correspondence is quite good.

SOME FILTER DESIGN CRITERIA

The three methods of filtering reviewed above (conventional, delay line, and digital filtering) are different ways of accomplishing general linear filtering. We will now review some of the recent developments in filter design criteria, or the reasons and justifications for selecting and applying a certain group of filter characteristics out of the infinite number available.

Figure 5 again shows the amplitude and phase response of a typical seismic amplifier and filter. The amplitude response, of course, describes the relative attenuation of frequencies passing through the system. The effect of this relative attenuation on an input signal is often referred to as amplitude distortion. Likewise, the phase response describes the relative phase shift introduced by the system. The familiar interpretation of the phase response is, of course, that the slope in any frequency interval determines the time delay of the filter for signals of those frequencies, and that the zero frequency intercept of a tangent line to this slope, and the deviation of the response curve from this line, determine the phase distortion. Figure 5 shows the effect of this amplitude and phase distortion (trace 2) on an input wavelet (trace 1). Notice the time delay, the change in

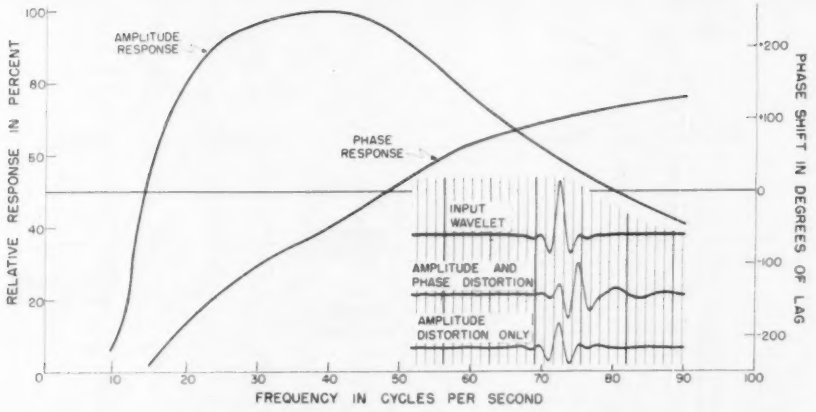

FIG. 5. Example of amplitude and phase distortion.

waveform, and the spreading or greater delay of the low frequencies with respect to the high frequencies. Trace 3 shows the effect of amplitude distortion alone. Here the resemblance to the input wavelet is quite striking. Thus, the major distortion of the wavelet must be attributed to phase distortion. The example shown in Figure 5 was, of course, selected to illustrate phase distortion and is therefore an extreme case. However, the seismic amplifier-filter used to obtain this example does represent a typical simple seismic system.

Zero-Phase Shift Filtering

The effect of phase distortion (illustrated in Figure 5) upon record interpretation and the accuracy of the results is a function of the system used and the characteristics of the seismic energy. In most cases this effect is minimized by restricting the number of filters used to a few closely related settings. Nevertheless, the high degree of similarity between input wavelet and output wavelet when only amplitude distortion is present, suggests the desirability of a seismic system with zero-phase shift at all frequencies. Magnetic recording can be used for this purpose, as shown schematically in Figure 6. The input wavelet (shown in the bottom left hand corner of Figure 6) is modified by the amplitude response, and its phase is shifted according to the phase response of the filter (top left hand corner of Figure 6). The wavelet emerging from the filter (second wavelet from the left) is then magnetically recorded. Now we recall that the effect of the filter phase shift was to delay, by different amounts, the various frequencies making up the input wavelet, thus causing phase distortion. Therefore, if the distorted wavelet is reversed, or turned around in time, and passed through the same filter, the filter phase shift will again delay these same frequencies as before, but the delay will be in the opposite direction with respect to the wavelet. Thus, the

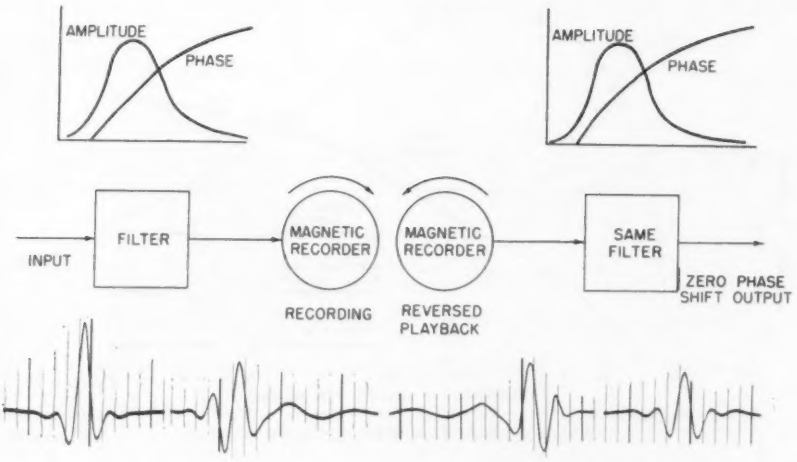

FIG. 6. Schematic diagram of zero-phase shift filtering.

additional delay will merely compensate for the previously introduced delay, and the total phase shift introduced by the forward recording and reverse playback will be zero. However, the amplitude responses will be multiplied, as would be the case if the wavelet were filtered normally through two filters in series. Referring again to Figure 6, the distorted wavelet is played back in reverse from the magnetic recorder (third wavelet from the left) and passed through the identical filter used in recording. The filter phase shift compensates for the phase distortion previously introduced, and the wavelet emerges (right hand wavelet) resembling the input wavelet except for the desired amplitude filtering. Although this method of filtering is known by a variety of names, we call it zero-phase shift filtering.

Figure 7 shows a portion of a conventionally filtered 12-trace record. Figure 8 shows the same record zero-phase shift filtered. Now it is well known that not only do the filter and amplifier introduce phase shift, but the seismometer as well has a phase and amplitude characteristic. Figure 9 shows the same record as in Figure 7, zero-phase shift filtered through the amplifier, filter, and electrical equivalent of the seismometer. Thus, no phase shift has occurred between the ground motion and the galvanometer.

Cross-Correlation Filtering

Cross-correlation filtering as applied to seismic data has been described by Jones and Morrison (1954). Briefly, cross-correlation filtering consists of searching a trace for the occurrence of an expected waveform by the mathematical (or electrical) operation of cross-correlating the trace with the expected waveform. This is fully equivalent to filtering the trace through a filter whose impulse response is the reverse of the waveform sought. This filter design criteria can be

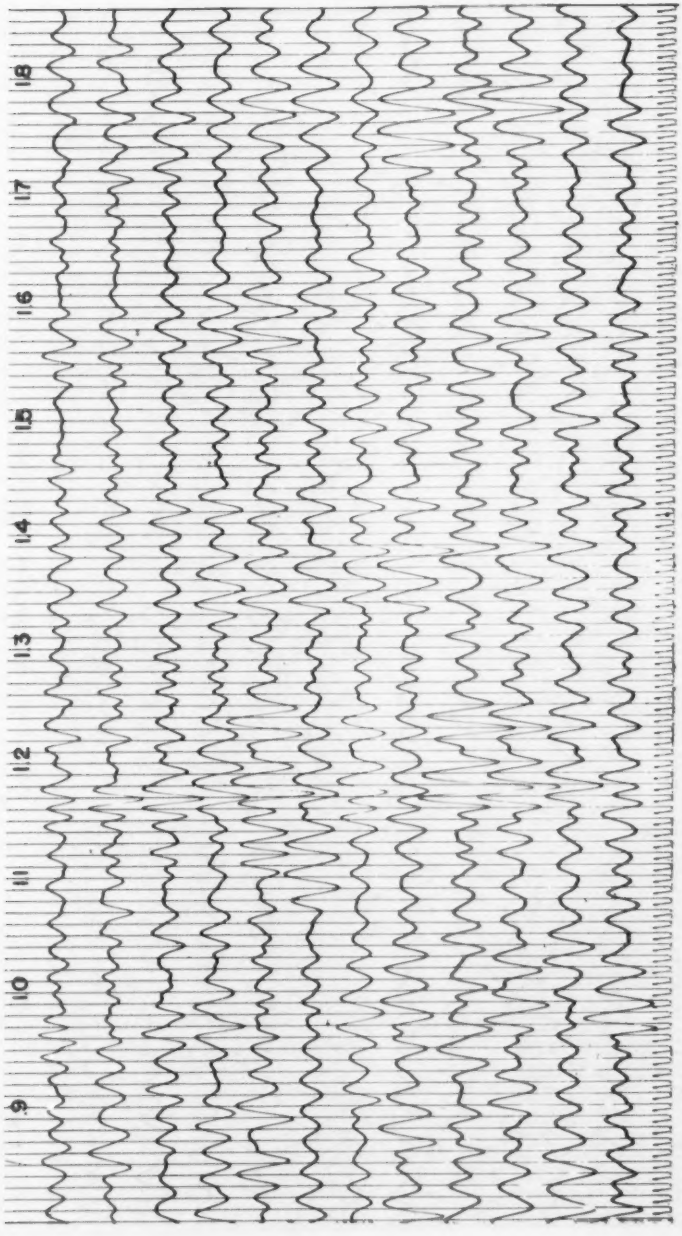

FIG. 7. Record A—Conventionally filtered.

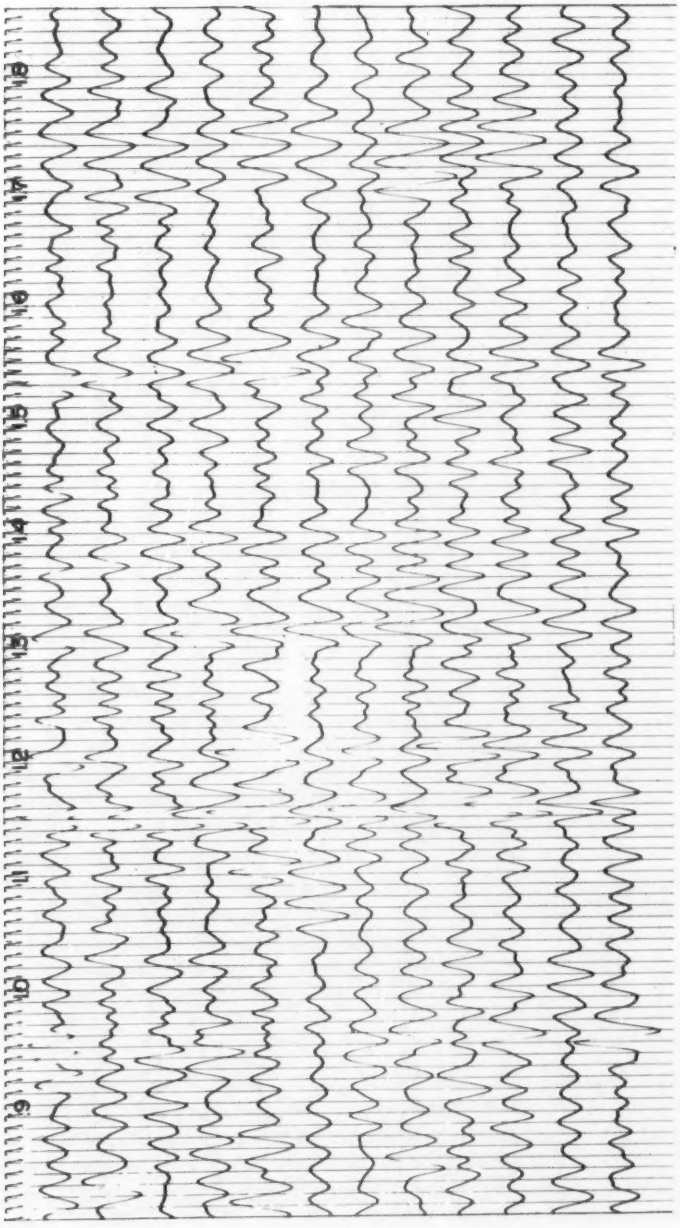

FIG. 8. Record A—Zero-phase shift filtered.

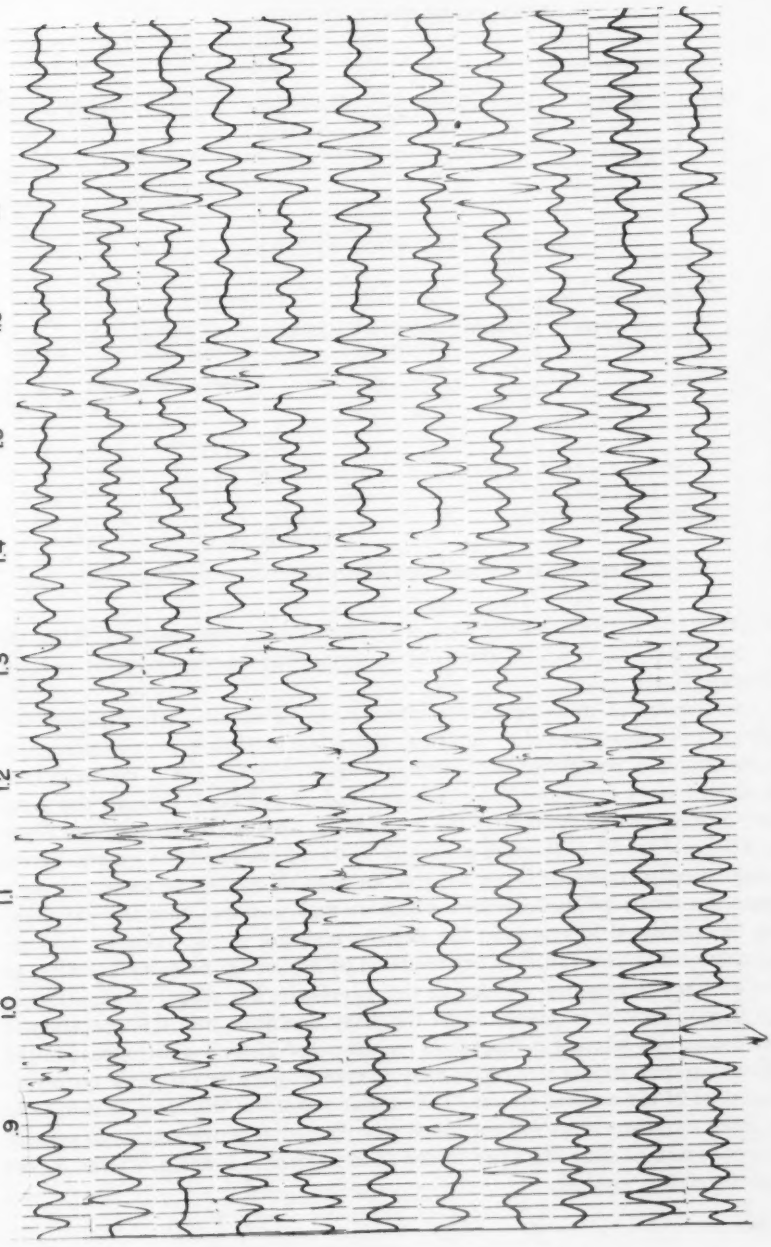

FIG. 9. Record A—Zero-phase shift filtered including seismometer, amplifier, and filter.

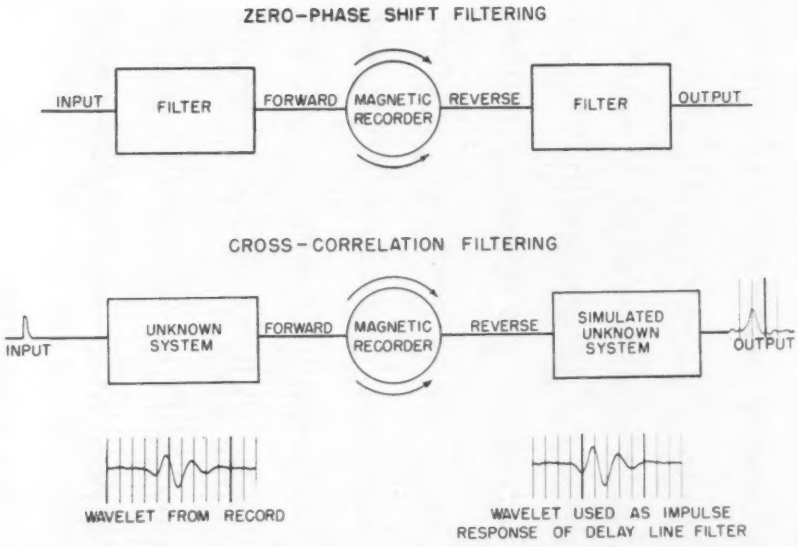

FIG. 10. Comparison of zero-phase shift filtering and cross-correlation filtering.

justified mathematically on the basis of maximizing the signal-to-noise ratio, for that particular waveform, if the noise is white (flat frequency spectrum) and Gaussian (North, 1943).

The concept of cross-correlation filtering can be more lucidly explained by analogy with zero-phase shift filtering. Referring to Figure 10, the schematic representation of zero-phase shift filtering is again shown in line 1. We recall that the filtered trace is magnetically recorded and played back through the same filter to compensate or eliminate the phase shift. Now in cross-correlation filtering, a seismic record containing a wavelet or waveform which we wish to detect is magnetically recorded. If we imagine an impulse applied to some unknown system has generated the waveform which we wish to detect, then the waveform may be considered to represent the impulse response of the unknown system. The unknown system can then be simulated by adjusting the delay line filter to have an impulse response simulating the waveform. The magnetic recording is then played back in reverse through the delay line filter, and this operation of cross-correlation filtering compensates for the phase distortion introduced in the unknown system just as zero-phase filtering compensates for the phase distortion introduced in the seismic system. The output waveform will then be similar to the input impulse except for the amplitude distortion of the unknown system. Figures 11 and 12 show the same record as in Figures 7, 8, and 9, filtered by the cross-correlation method.

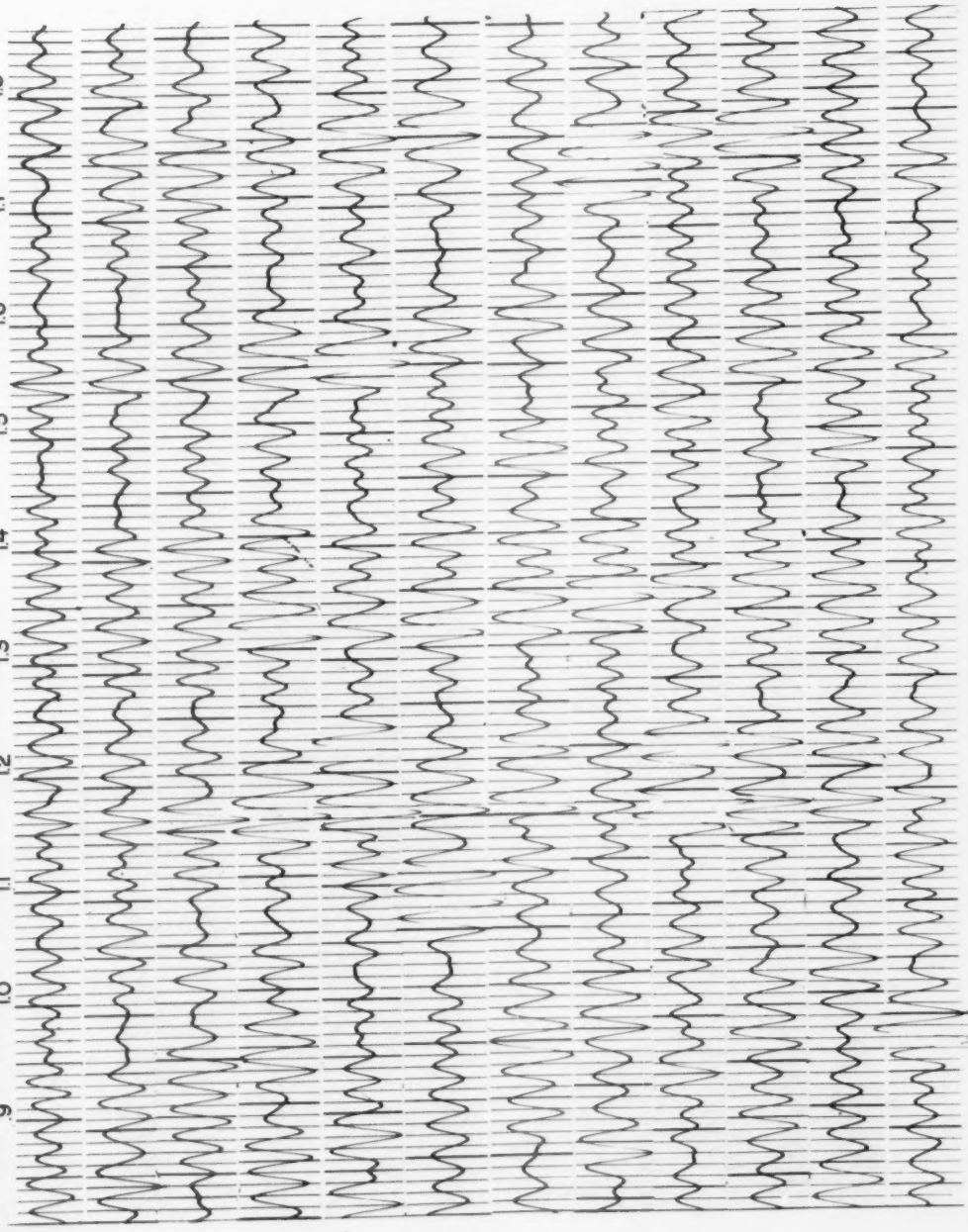

FIG. 11. Record A—Delay line filtered using cross-correlation criteria X.

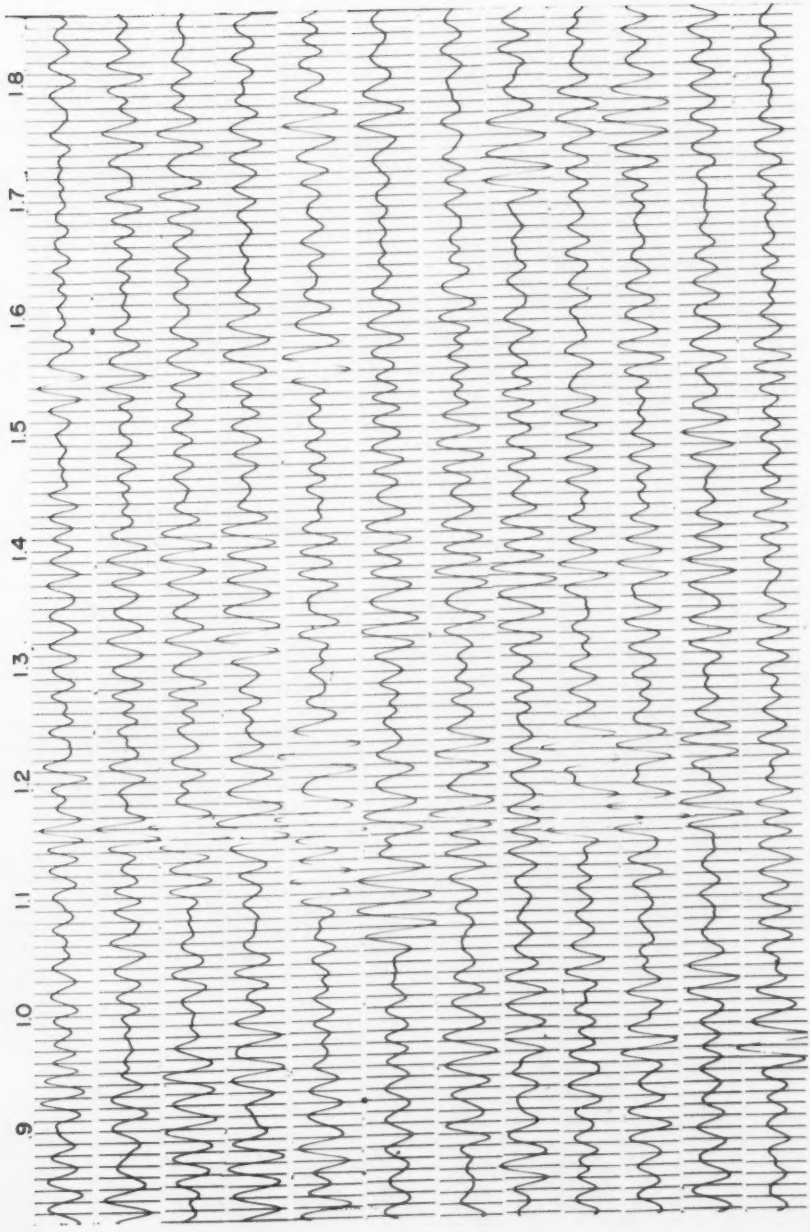

FIG. 12. Record A—Delay line filtered using cross-correlation criteria Y.

CONCLUSIONS

The objective of this paper has been to review and clarify methods of filtering seismic data. The record examples shown were not selected to prove that one method is superior to another or that any practical improvement can be gained by these techniques. Rather, the examples are included solely as illustrations of these filtering techniques.

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GEOPHYSICS, VOL. XXIII, NO. 1 (JANUARY, 1958), PP. 58–80, 22 FIGS.

SEISMIC REFLECTION RECORDS OBTAINED BY DROPPING A WEIGHT*

EDWIN B. NEITZEL†

ABSTRACT

Measurements of the wave shape of the seismic transient generated by dropping a weight indicate that the weight drop has a much higher efficiency than shooting dynamite. The surface wave which is generated by the weight drop is very large, but it is minimized by the use of large seismometer groups, many drops per trace, and large offset distances. For experimental studies, a special recording instrument adaptable for either shooting or weight dropping is used. The weight truck is hydraulically operated. Weight dropping versus shooting studies indicate that the quality of weight drop records is limited by the large surface wave generated by the weight impact on the ground.

INTRODUCTION

During the pioneer days of seismic prospecting, seismic transients were generated by dropping a weight on the ground surface for experimental studies. The large surface noise generated by the weight impact resulted in discouraging results.

Because of the advancements in instrumentation during the last few years, this picture has been changed considerably. This is due primarily to the development of magnetic recording as a useful seismic tool.

If a large number of samples of signal plus noise data are accumulated, a well known process can be applied. If the signal or reflection events have strong coherence but the noise has low coherence, the summation of the recordings will result in an improvement in signal-to-noise ratio. Dr. Burton McCollum (1956) was a distinguished pioneer in the application of this principle to seismic prospecting.

BASIC EXPERIMENTS

In a study of weight dropping, the first subject of importance is the seismic transient generated by the weight impact on the ground. Consider first the seismic transient amplitude.

Seismic Transient Amplitude

The energy in a pound of dynamite is approximately 2,300 B.T.U.'s. By dropping a 4,600 pound weight from 9 feet, 53 B.T.U.'s of potential energy are available. A small percentage of this energy is expended due to wind resistance during the fall, but the assumption is made that all the energy is kinetic at the instant of ground contact. In West Texas, a pattern shot was compared with one drop of this weight, and the Devonian reflection amplitude was measured with

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FIG. 1. Model dropping instrument for letting a 240 pound weight slide down a steel pole to contact a base plate.

calibrated equipment. The 36 hole pattern shot consisted of 205 pounds of dynamite (475,000 B.T.U.'s) which gave a Devonian reflection amplitude, normalized as one. The one weight drop resulted in a reflection amplitude of one-third of this value. From these values, it can be concluded that the efficiency of the weight drop was approximately one thousand times the efficiency of the dynamite shot.

Other important factors to be considered are the wave shape of the seismic transient and the seismic noise which is generated by the weight impact.

Seismic Wave Shape

Generation of seismic energy in the elastic ground calls for a detailed study of many factors. Consideration must be given to the mass, the velocity, and the

shape of the falling body as well as the elastic constants of the weight and the ground.

Lamb (1904), Jones (1946), Prescott (1946), and a few others in the past have discussed analytically the impact of a force with a semi-infinite solid body. Recently Evison (1951), Miller and Pursey (1954), Newland (1954), Pinney

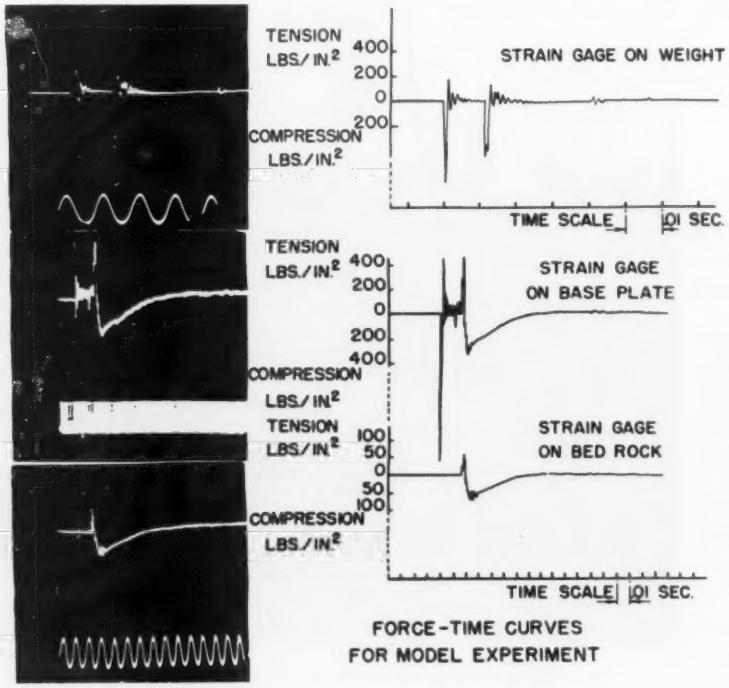


FIG. 2. Strain gauge data obtained with model dropping instrument.

(1954), and Kasahara (1954) have discussed analytically the generation of seismic energy due to the application either of force or of the impact of a falling body to the solid semi-infinite medium.

These theoretical approaches are difficult to verify by field experiments because of such complicating factors as the crushing of the near surface for a short time after the weight impact. But, it is an interesting and important point to illustrate the general characteristics of the seismic transient. For this reason, a study was made of the seismic transient by the use of strain gage measurements which agreed with the analytical work in a very approximate manner.

Figure 1 shows a model dropping instrument which was used for allowing a

240 pound weight to slide down a steel pole and contact a base plate. By letting the weight slide down the pole, the same transient was produced with each drop of the weight. Strain gages were mounted on the weight, on the base plate, and in the ground.

Figure 2 shows some of the data which were obtained. The sine wave curves were calibration curves and the actual data were obtained by photographing the face of an oscilloscope tube.

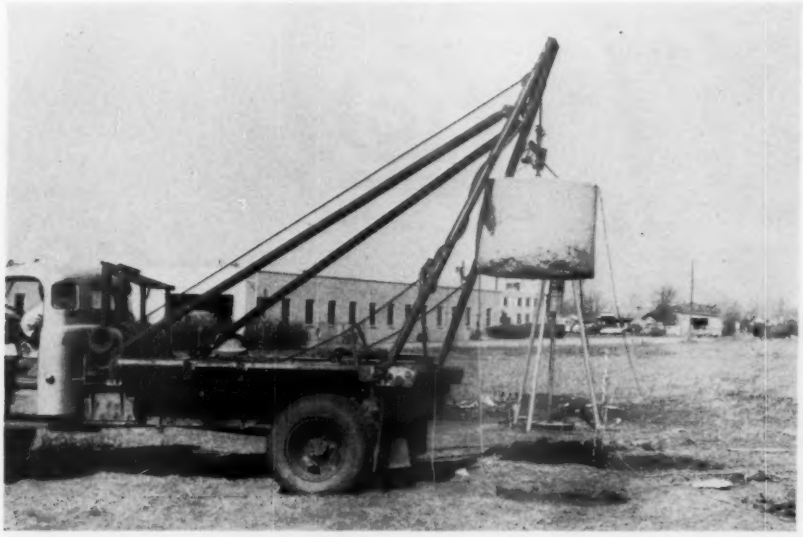


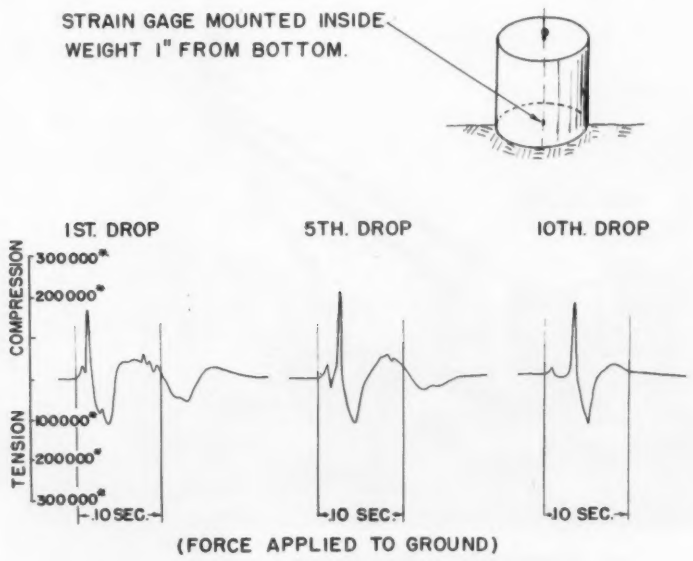
FIG. 3. Apparatus for obtaining strain gauge data with 4,600 pound weight.

Frequency response of the system was 5 to 2,000 cycles per second. Actual data are reproduced at the right for clarity. Notice from the strain gage on the weight, shown at the top, the first impulse is an impulse in compression when the weight contacts the base plate. The base plate bounces away, and a short time later the weight contacts the base plate again. At this time it couples a seismic transient into the ground. Note the wave shape of the seismic transient which is in the ground, shown by the strain gage on the bedrock. Analytical expressions and explanations of the complete data were inconclusive. The important point to note from these measurements is the time scale, for the seismic transient is approximately 1/20 of a second long. It is very long compared to the seismic transient resulting from a dynamite detonation, so that the predominant frequency for a weight drop is low compared to dynamite shooting.

Figure 3 shows the apparatus which was used for dropping a 4,600 pound

concrete block on the ground. Strain gages were mounted on the weight and in the ground.

Figure 4 shows some of the data obtained with this apparatus. With the strain gage mounted inside the weight one inch from the bottom, using the elastic constants of concrete, a force-time curve was obtained at the surface of the ground. These measurements were obtained with calibrated seismic instruments with a frequency response from 8 to 150 cycles per second. Note, for the first



FORCE-TIME CURVES AT BOTTOM OF CONCRETE WEIGHT.

FIG. 4. Strain gauge data using a 4,600 pound weight.

drop, the recording shows an impulse in compression of 200,000 pounds which is followed by a low frequency oscillation. By continuing to drop in the same location, compacting the ground, and then recording the latter drops of the weights, we notice a decrease in the low frequency oscillation. In some areas it is advantageous to compact the ground before recording.

TECHNIQUE

Consider now a simplified weight drop technique for 10 drops per trace with 50 percent ground overlap. This will illustrate the process for building up a com-

posite record and the process could logically be extended to any number of drops per trace or any degree of overlap. Each end of a spread of weight drops contains a group of 64 seismometers. Figure 5 identifies these as seismometer group no. 1 and seismometer group no. 2. The surface of the ground or dropping spread is laid off into six intervals; intervals A through F. The weight truck starts dropping at the beginning of interval A, and each time the weight drops a recording is made on magnetic tape from seismometer group no. 1 and from group no. 2.

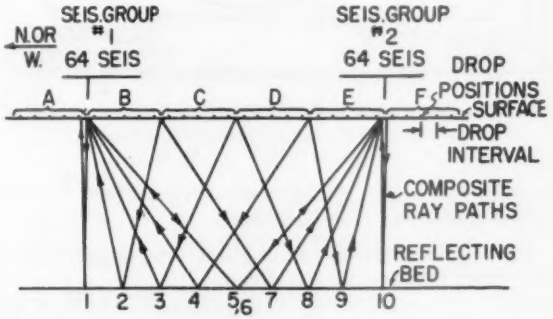


FIG. 5. Simplified weight dropping technique for ten drops per trace with 50 percent ground overlap between traces.

The weight truck proceeds through interval B to pick up ten recordings from each of the seismometer groups. After the completion of the tenth recording, an addition of the magnetic tracks is made with the reflection events aligned. Addition of the data from seismometer group no. 1 gives trace no. 1 corresponding to subsurface coverage point no. 1. Addition of the data from seismometer group no. 2 gives trace no. 6. The weight truck then proceeds to pick up five more drops at interval C. Retaining the information in interval B and adding on the information from interval C, subsurface coverage point no. 2 is obtained from the addition of data from seismometer group no. 1. Subsurface coverage point no. 7 is obtained when the addition is made from seismometer group no. 2. The weight truck then proceeds down the line to pick up the drops necessary for building up the composite multi-trace record.

You will notice that traces 5 and 6 are the corresponding tie traces for a conventional split recording. Traces 1 and 10 correspond to the conventional computing traces or zero offset traces of a split record.

EQUIPMENT

The type of equipment used for weight dropping is dictated by the primary object of the work. Equipment which will be briefly described was designed primarily for experimental use.

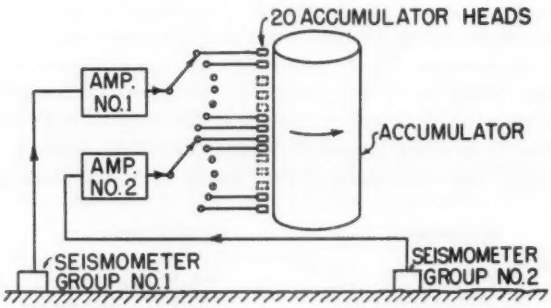


FIG. 6. Recording of individual drops in the field. Each drop is recorded on the magnetic drum through a different pair of heads.

For experimental equipment, a fundamental requirement is versatility. General features of the equipment are listed below:

Function	Conventional shooting recording or weight drop recording.
Tape recorder	FM magnetic recording.
Number channels	One or two channel recording for weight dropping.
Capacity	Maximum number of drops/trace = one hundred.
Corrections applied	Fixed time shifting of magnetic recording. (Normal move-out corrections not applied by the use of the field equipment.)

The process of recording could be divided into three basic steps as described below. The first of these steps as shown in Figure 6 is the recording of the one-trace or usually two-trace data on a magnetic drum. The signal from seismometer group no. 1 passes through amplifier no. 1 and is recorded onto an appropriate magnetic head position. Similarly, the signal from no. 2 is recorded on an appropriate magnetic track position for the second channel. After each drop another magnetic track position is turned on until we have completed ten positions for each channel. The next step, which is illustrated in Figure 7, is the integration or the storage of the recorded data.

Information from the ten magnetic track positions with the reflection events aligned is played back through adder no. I and recorded on an appropriate magnetic storage track position for building up the final composite record. Similarly, the data from adder II are stored for building up the final composite record. By continuing this process, our final composite record is constructed. The final step in the process is the playback of the final ten trace record onto a standard oscillograph camera. See Figure 8.

There are two approaches for the three steps which can be considered. One can perform all of these operations in the recording truck in the field. The alternative is to perform the basic recording and some of the additions in the field, but the final additions and playback of the data would be from a central office

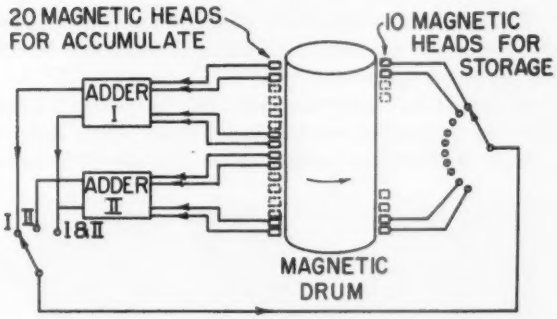


FIG. 7. Addition of the single drop recordings.

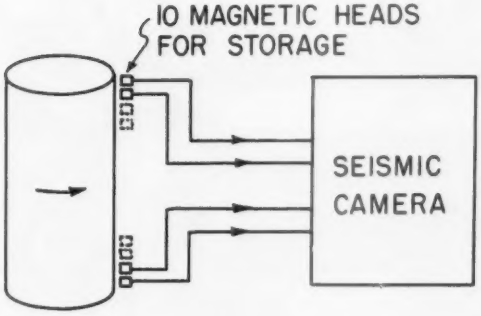


FIG. 8. Playback of the final composite record.

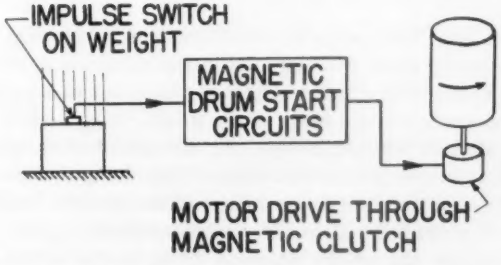


FIG. 9. Method of obtaining time alignment for the reflection events. Record starts at instant of weight impact on the ground.

machine. The first approach is versatile and inexpensive, and this makes it easily adaptable for experimental purposes. For production work the central office playback approach results in higher efficiency.

The step which has not been considered in the previous discussion is the method of obtaining time alignment for the reflection events. Referring to Figure 9, when the weight contacts the ground, an impulse switch attached to the top

FIG. 10. Weight dropping truck shown with the dropping mechanism folded up. Weight rests on the truck bed for transporting.

of the weight closes. This causes one time-break to be propagated over a radio link to the magnetic drum start circuits in the recording truck. These circuits energize a magnetic clutch which results in the initiation of drum rotation. Therefore, the record starts at the instant of the weight impact on the ground.

Initiation of drum rotation is obtained with an effective starting time of 10 milliseconds by the use of a special design. This design consists of a magnetic clutch, a compliance coupling, and a follow-up mechanism. Accuracy in starting times of plus or minus one millisecond was maintained.

Figure 10 shows the weight dropping truck in the folded position. A hydraulically operated ram is used for raising the weight dropping framework. After the framework is in the raised position, it is locked automatically by a

hydraulically operated lock pin. Figure 11 shows the framework in the dropping position. The weight is raised by a quadruplex cable system within the bed of the truck, so that a short stroke cylinder could be used. A solenoid-controlled dropping valve opens a large area drop valve resulting in low back resistance to the falling weight. Design of the structure is such that it can be easily transferred from one truck to another. The weight is made of case Kirksite which was used

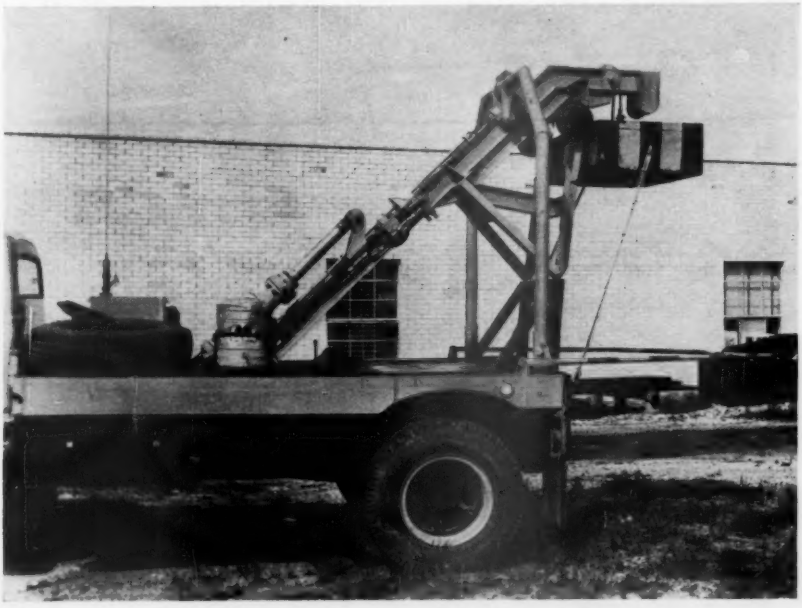


FIG. 11. Weight truck with framework in the dropping position.

because of its high salvage value and its ease of procurement. High impact strength of Kirksite was also an important factor. Weight was 5,300 pounds.

EVALUATION

Number of Drops per Trace

Figure 12 illustrates a laboratory controlled example of the improvement in signal-to-noise ratio by the process of adding many samples of the same signal in different samples of random noise. Noise for these tests was generated by a noise generator and then passed through a seismic amplifier filter with a pass band of 8 to 150 cycles per second. In general, a conclusion from well-known signal detection theory is that the improvement in signal-to-noise ratio is proportional to the square root of the number of samples when the signal is coherent and the

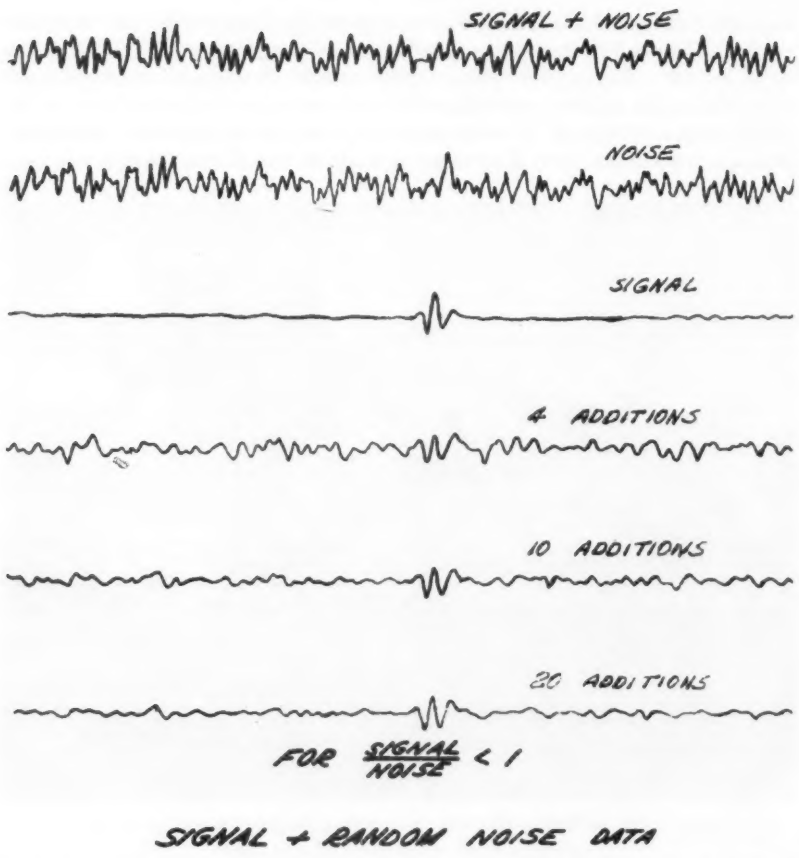


FIG. 12. Laboratory experiment to illustrate the improvement in signal-to-noise ratio by the addition of samples of the same signal superimposed on different random noise.

noise is incoherent. For the field case the noise is not random in nature, but the seismic signal is often more coherent than the seismic noise.

Figure 13 illustrates how the detection of seismic signals is increased by increasing the sampling process. These records were obtained in West Texas with zero ground overlap.

Shooting Versus Weight Dropping

It is always difficult to evaluate a seismic tool. In one area excellent results may be obtained. The next area may result in the opposite conclusion. A question

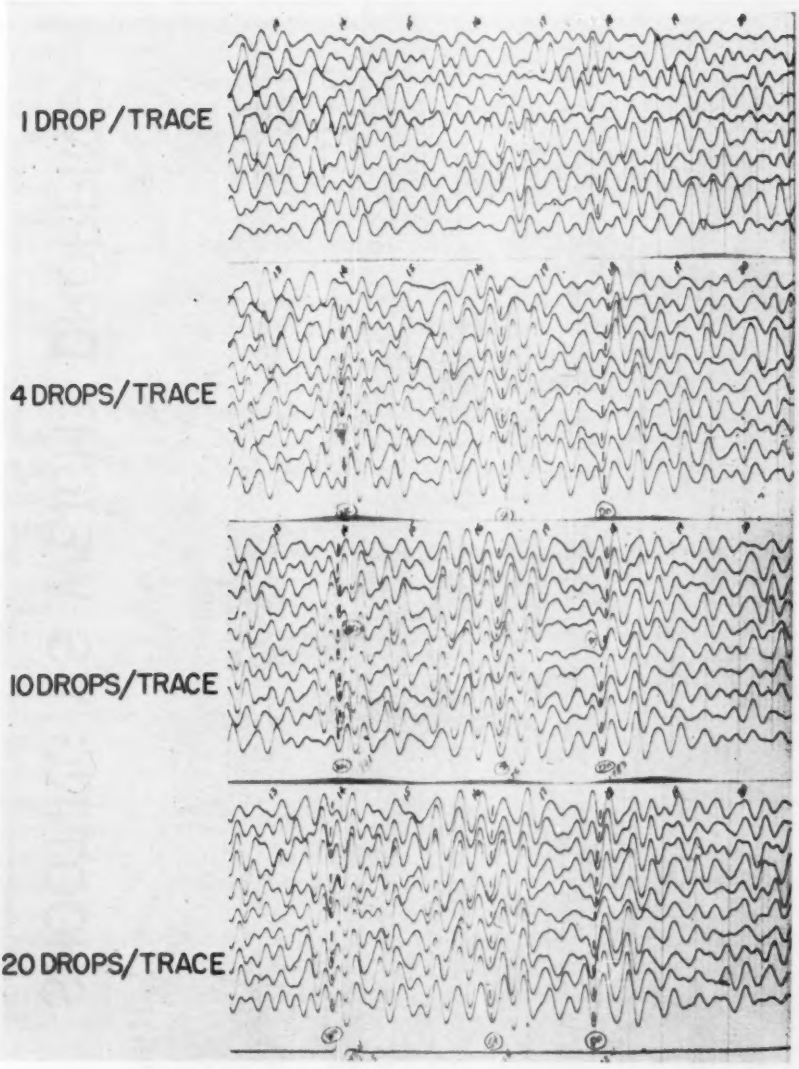


FIG. 13. Field data illustrating the improvement in signal detection by the use of different number of drops per trace.

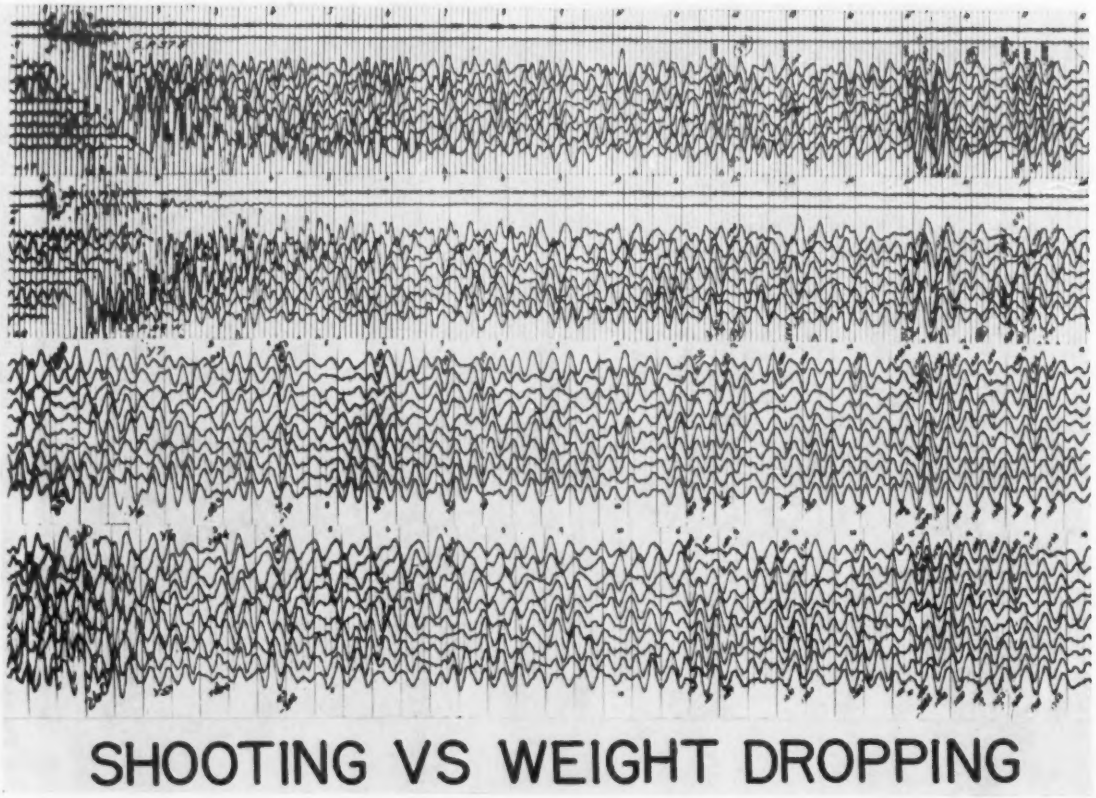


FIG. 14. Comparison records for shooting versus weight dropping. Top two records—shooting records. Bottom two records—weight dropping records.

is often asked, "Are the optimum weight drop records for an area better than the optimum conventional shooting records?" The answer is usually, "No." At this point it must be admitted that the cost of obtaining the weight drop records is usually much less than the conventional shooting data. So, how good should the data be before the geophysicist will use it? Some very general conclusions concerning an evaluation are illustrated on Figure 14.

The top two records were obtained with multiple hole shooting, and the bottom two records are the approximate equivalent weight drop records. Notice immediately that the deep reflections in the shooting records have better reflection standout than the weight drop records. This has been found to be generally true. Does the additional reflection standout justify the high cost of shooting? The geophysicists usually answer, "Yes, because we need high reflection standout for character identification. And furthermore, we want better record quality than we are getting with the best conventional shooting techniques."

Figure 15 shows an interval of a record section which gave good reflection standout for the primary reflection of interest, the Siluro Devonian. These records were corrected to a plane, and normal moveout was removed by the use of a central office tape playback machine (normally used for conventional seismic record tape playbacks). Other reflections on the records could be emphasized by playing back the records with more gain and a stronger AGC action.

If the best weight drop records are not as good as the best conventional shooting records, an explanation should be sought. In an area in West Texas, some poor, fair, and good weight drop records were obtained. In an attempt to evaluate why the poor records were obtained, numerous experiments were performed, and one of these was a ground-roll test. Figure 16 shows the ground-roll records which were obtained at the locations where some poor, fair, and good records were obtained. The filter setting for obtaining these records was the narrow band filter which was normally used for weight dropping in the area. Records were obtained by dropping the weight one time at a distance of 700 feet from the seismometer patch and recording one drop per trace, so that the information is almost entirely ground roll. A one drop per trace record was obtained by equally spaced in-line drops as the weight truck moved out from the seismometer patch. Notice on the top record that ground roll carry-out is for the entire length of the record. At the location where a fair reflection record was obtained, there is less evidence of carry-out for the ground roll as illustrated by the second record. At the bottom of Figure 16, there is very little evidence of ground roll after approximately one second, and a good reflection record was obtained at this location. This evidence illustrates that the surface noise is the primary problem. This can be further substantiated by measurements of surface-noise amplitude in the ground around the drop points. In Figure 17 the poor, fair, and good records corresponding to those locations are illustrated.

In order to obtain the optimum weight drop technique, the various parameters which are used for building up the composite record must be investigated

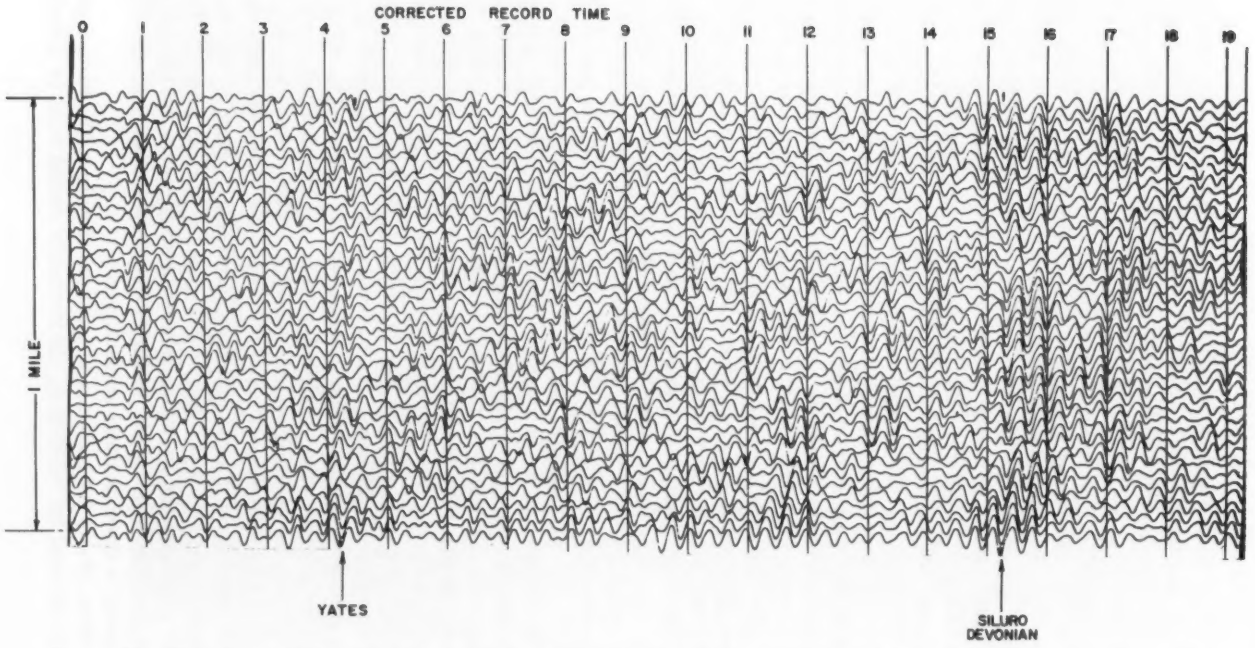


FIG. 15. West Texas Record-Section. Ten drops per trace, 50 percent ground overlap. Corrections to a plane with normal move-out removed.

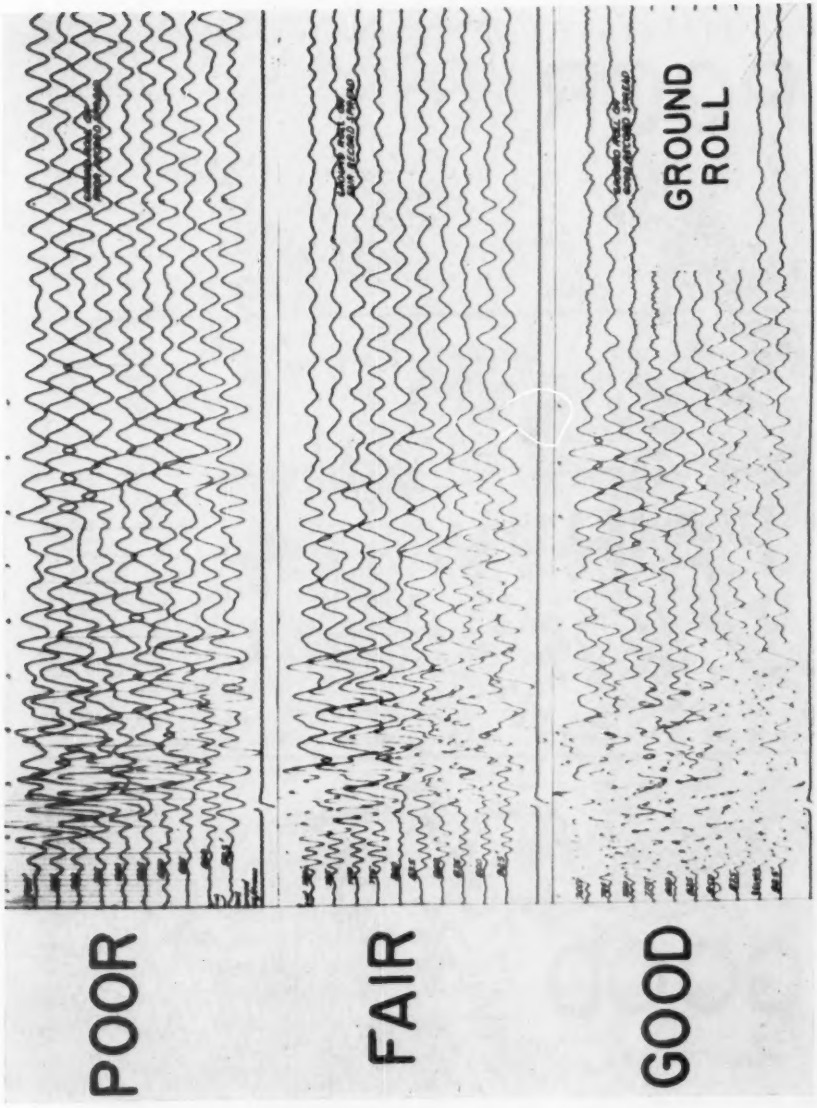


FIG. 16. Ground-roll test at locations where poor, fair, and good records were obtained.

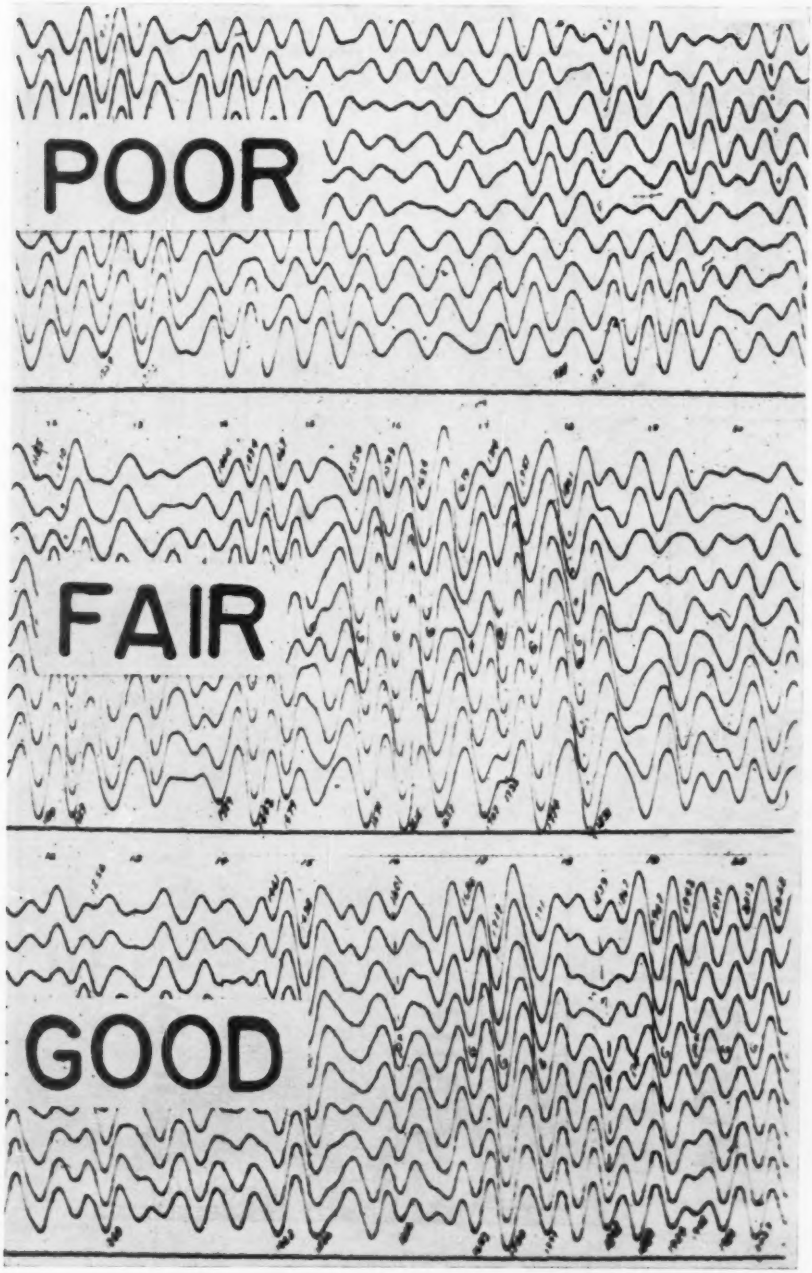


FIG. 17. Poor, fair, and good reflection weight drop records obtained at the locations for the ground-roll tests shown on Figure 16.

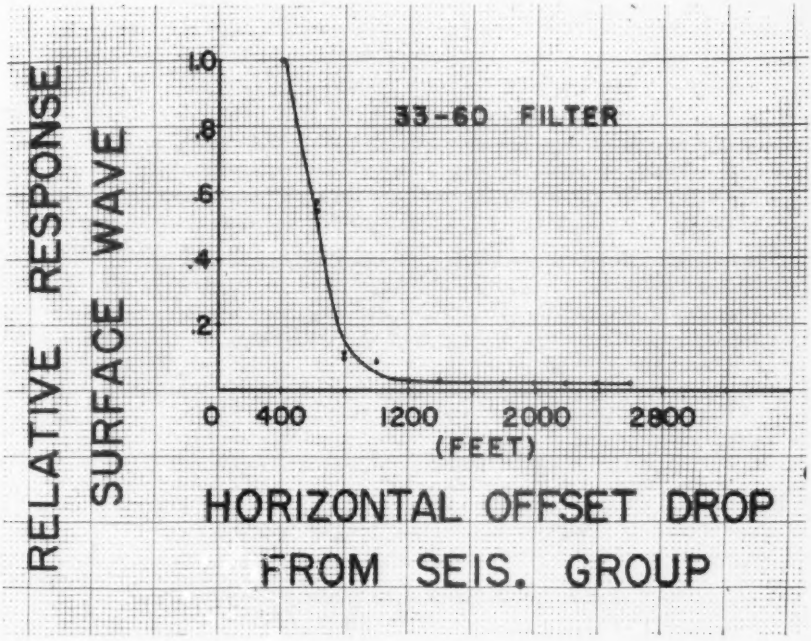


FIG. 18. Surface wave amplitude versus horizontal offset-drop to the seismometer group distance. Seismic amplifier filter setting 33–60.

to check the effect on the recorded surface noise. In approximately the same location as the ground-roll test described above, several curves were obtained and are described below.

Surface Wave Versus Horizontal Offset-Drop from Seismometer Group

It is a well known fact that ground roll is attenuated with increasing offset due to the geometrical factor, the attenuation of the ground, and the particular near-surface elastic layering conditions. Data for Figure 18 were obtained with one drop per trace, so that primarily surface noise was observed. Measurements were made with calibrated equipment through a narrow band filter of 33–60. Notice considerable attenuation of ground roll with increasing offset. Advantage can be taken of this improvement in some areas.

Surface Wave Versus Circular Seismometer Pattern Diameter

In carrying out seismic field work there are numerous arrangements for seismometer groups which may be used. Analytical considerations of the horizontal response to the predominant ground roll frequencies should dictate the particular

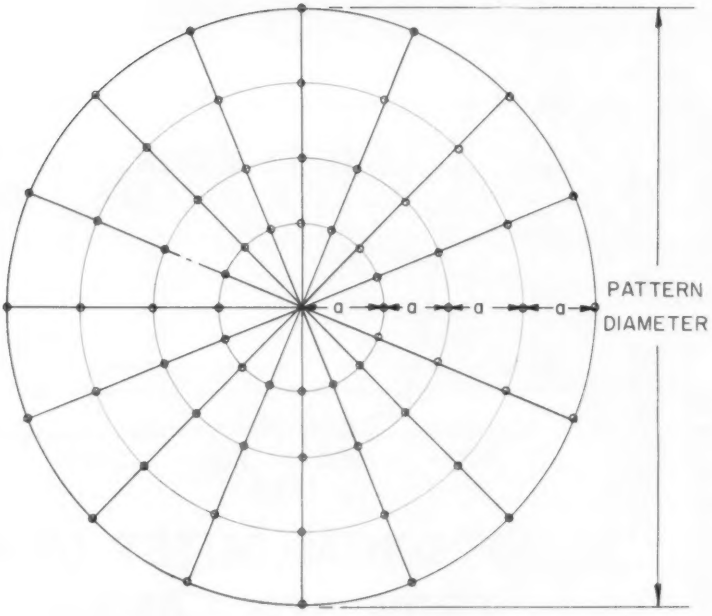


FIG. 19. Pattern dimensions for 64 seismometer pattern.

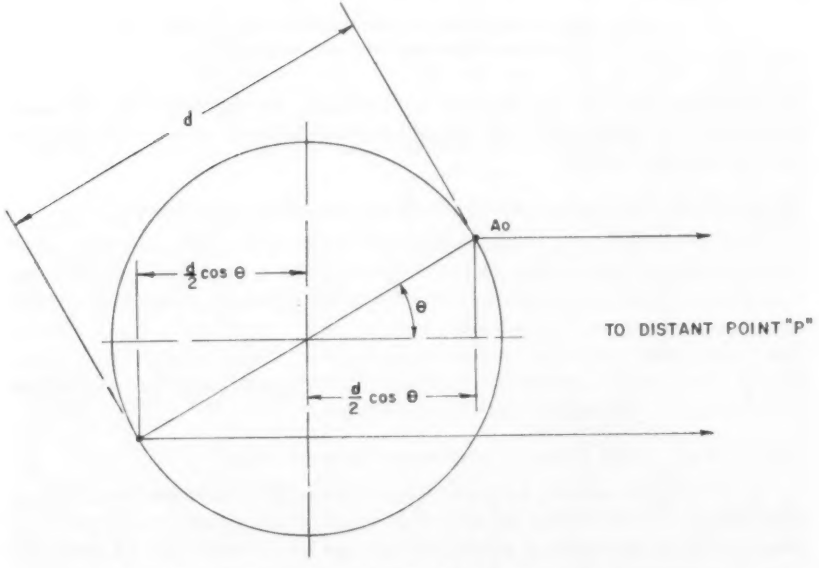


FIG. 20. The geometrical relationship leading to equation 4.

arrangement. This analytical work should act as an aid to decrease the amount of field experimentation required for solution to a particular problem. Both theoretical work and the practical aspects of routine field operation led to the development of a circular seismometer array of seismometers. Results for this array are illustrated by a comparison of field experimentation versus theoretical response.

For the following curve the number of seismometers per pattern was held constant at 64, and the pattern area was varied to determine the relative response to the surface wave. Pattern dimensions are given on Figure 19. Assuming that this pattern can be approximated by four concentric continuous ring seismometers, a theoretical curve can be computed for comparison with the experimental measurements. Assume also that the pattern dimensions are small compared with the distance between pattern and drop point, as illustrated by the parallel ray paths on Figure 20.

The amplitude at P due to the two incremental units of strength A_0 on the ring is

$$\begin{aligned} A &= A_0\epsilon^{-j(\psi/2)} + A_0\epsilon^{+j(\psi/2)} \\ &= 2A_0 \cos\frac{\psi}{2}, \end{aligned} \tag{1}$$

where

$$\psi = d_r \cos\theta,$$

and

$$d_r = \frac{2\pi d}{\lambda}.$$

Integrating to get the effect of the entire loop,

$$\begin{aligned} A_t &= 2A_0 \int_0^{\pi} \cos\frac{\psi}{2}\, d\theta; \\ A_t &= 2A_0 \int_0^{\pi} \cos\left(\frac{d_r}{2}\cos\theta\right) d\theta = KJ_0\left(\frac{\pi df}{v}\right); \end{aligned} \tag{2}$$

where

$$K = \text{constant} \tag{3}$$

and

$$J_0\left(\frac{\pi df}{v}\right)$$

is a zero order Bessel Function.

If the four rings of Figure 19 have diameters of d_1, d_2, d_3, and d_4, then the

Relative response

$$= K\left[J_0\left(\frac{\pi d_1 f}{v}\right) + J_0\left(\frac{\pi d_2 f}{v}\right) + J_0\left(\frac{\pi d_3 f}{v}\right) + J_0\left(\frac{\pi d_4 f}{v}\right)\right]. \qquad (4)$$

By assuming a linear system the principle of reciprocity allows either the ring or the point P to be the radiator or weight drop. For this particular application the point P would be the weight drop position.

Correlation between the computed and the theoretical curve of Figure 21 is relatively good. The measured frequency and velocity that were used to obtain the computed curve were 20 cycles per second and 5,000 feet per second.

Surface Wave Versus Length of Drop Pattern

From antenna theory, Kraus (1950), the in-line response of an in-line array of equally spaced drops is given as the relative response,

$$A = \frac{1}{2}\,\frac{\sin\dfrac{nd_r}{2}}{\sin\dfrac{d_r}{2}}, \qquad (5)$$

where

n = number of drops,

d_r = angular distance between drop positions

$= (360)df/v$,

d = distance between drops in feet,

f = frequency in cycles per second,

and

v = velocity in feet per second.

For the computed curve of Figure 22, velocity of 5,000 feet per second and frequency of 20 cycles per second were used, and we held the number of drops per pattern constant at 20.

CONCLUSIONS

By dropping a weight, a seismic wave can be efficiently generated. When the weight contacts the surface a large amount of surface noise is also generated. This noise must be minimized before reflections can be mapped.

In order to minimize the noise on the final composite record, numerous parameters can be worked with. A large number of drops per trace, the proper size seismometer groups with an adequate number of seismometers, and the correct filter settings for both record and playback are necessary in order to obtain a satisfactory record.

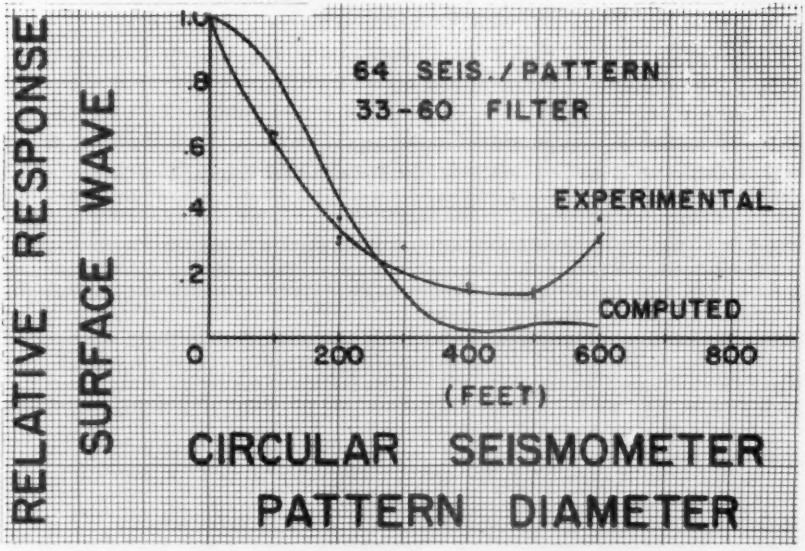


FIG. 21. Surface wave amplitude versus seismometer pattern diameter of Figure 19. Computed curve obtained by using equation 4.

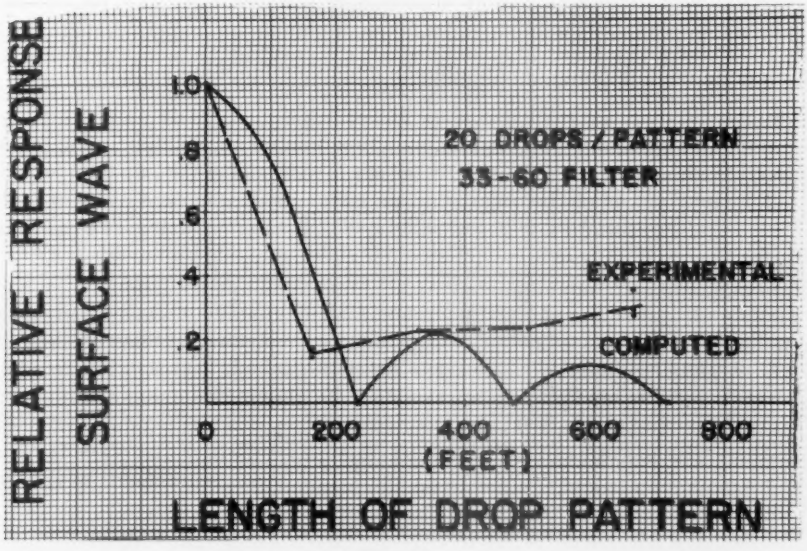


FIG. 22. Surface wave amplitude versus length of drop pattern. Computed curve obtained from equation 5 using a frequency of 20 cycles per second and a velocity of 5,000 feet per second.

ACKNOWLEDGEMENT

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GEOPHYSICS, VOL. XXIII, NO. 1 (JANUARY, 1958), PP. 81–96, 15 FIGS.

DIRECTIVITY EFFECT OF ELONGATED CHARGES*

A. W. MUSGRAVE,† G. W. EHLERT,† AND D. M. NASH, JR.†

ABSTRACT

After years of development it has been determined that the energy from the detonation of a low velocity explosive in an elongated column approaches a unidirectional pattern. This column is placed in the subweathering material extending ½ to 2 wavelengths in lengths depending on the frequency of energy desired.

A study of the theory of propagation showed that greater directivity can be obtained from the same length of charge by using a powder with a detonation rate less than the side wall velocity of the shot hole. As the detonation rate of the column is lowered relative to the side wall the directivity increases and the downward energy decreases. The optimum balance of these factors is a detonation rate about ⅓ of the side wall velocity.

Experiments on elongated charges indicate that a very important effect of directivity is the elimination of "ghosts" as well as the reduction of horizontal energy.

Interpretation may be greatly facilitated by a reduction in unwanted energy. Character is no longer dependent upon hole depth. Records have a more uniform appearance. Elongated charges produce many of the same effects as shallow pattern holes, but under many circumstances they are easier or less expensive to use.

INTRODUCTION

For some time it has been thought that a vertically elongated charge, properly delayed and detonated, would have properties of great value to seismic exploration. Previous papers gave the results of using a spiral primacord delay line to propagate the detonation of charges at the rate of the side-wall velocities in a borehole (Shock, 1950). The pressure field around distributed charges and their application to some seismic problems has been studied (Sparks and Silverman, 1953). The most important property expected of vertically distributed charges is their ability to radiate greater amplitude disturbances in the downward rather than in the upward direction. This property should greatly reduce the relative amplitude of many of the interfering reflections on a seismogram. The multiple reflections from energy initially reflected above the level of the shot have been dubbed "ghosts" (Van Melle and Weatherburn, 1953).

All of the early experiments with elongated charges used a prima-cord delay line, as described by Shock, to make the propagation velocity of the explosive equal to the acoustic velocity of the surrounding formation. The authors' experiments with this type delay line encountered great difficulty in obtaining complete detonation of charges of effective length under conditions slightly less than the ideal. These early charges were also cumbersome and their preparation was too time-consuming. For these reasons, an important aim of this experimental work was to develop a vertically distributed explosive that was operationally feasible as well as theoretically desirable.

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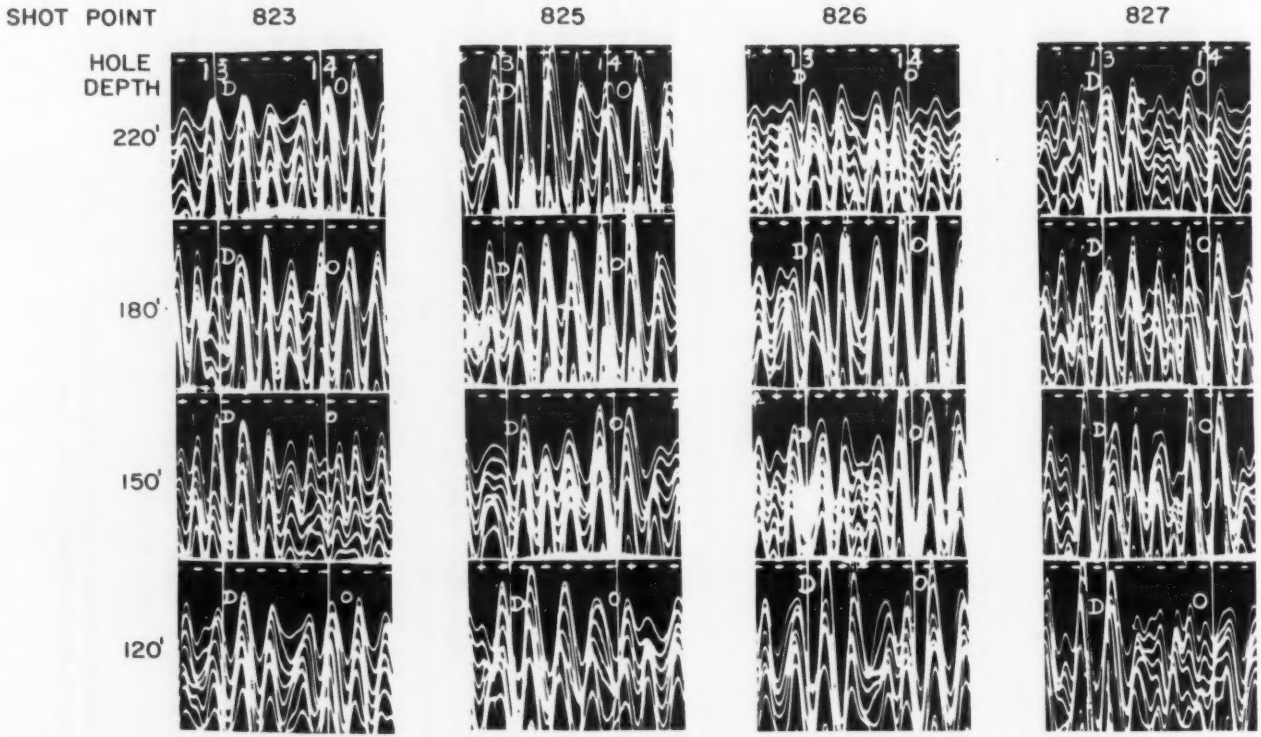

FIG. 1. Effect of ghosting on the character of the Devonian and Ordovician reflections in West Texas showing the reinforcement, distortion, and cancellation of the Ordovician reflections by the Devonian ghost.

EFFECT OF GHOSTING

An example of the need for a vertically distributed charge is found on records taken during a seismic survey made in West Texas in 1948. Figure 1 shows some of these records taken at four different shot points. The changes in relative phase and amplitude of the Devonian and Montoya (Ordovician) reflections with hole depth make correlations difficult. These character changes were caused by interference from ghost energy. The Montoya reflection was either reinforced or destroyed by the Devonian ghost. The only method then available to make the Montoya pickable was to find the shot depth in each hole at which reinforcement occurred. This hole depth depended on three factors, (1) uphole time, (2) time interval between the two horizons, and (3) the frequency and pulse width of the reflections involved. These factors made it impossible to find a depth in all the holes that was optimum for all the reflections on the records. The interpreter could allow the ghosts, more than the actual dips of the formations, to influence the map made from his interpretation.

Interference from ghosting has not been given proper recognition in the Louisiana Gulf Coast Area. This probably resulted from the discontinuity of reflections and the accepted absence of correlations. Figure 2 shows a portion of a group of records from southern Louisiana taken from shots coming up a hole at ten-foot intervals. A visual inspection of these records does not reveal the presence of ghosting but does clearly show some form of shot-hole variable. Figure 3 shows a statistical evaluation made by picking all peaks and troughs on all the records within the same time interval shown in Figure 2. These time picks were corrected to a surface datum and plotted against shot depth. Figure 4 is a generalization of this diagram. All picks that fall approximately on a vertical line are reflections. Those picks that approximate a line parallel to the plot of twice the uphole time are ghosts. This procedure reveals that nearly half of the information in this time interval on these records is meaningless. Figure 5 shows the relative quality of the data plotted on Figure 4. On records taken below a depth of 50 feet, many of the good lineups are the result of reinforcement of reflections by ghosts. A detailed examination indicated that almost every variation of reflection time observed on this set of records was due to the interaction of reflections and ghosts from shallower reflectors.

Figure 6 shows the effect of the ghost at 18 shot-hole depths ten feet apart in South Central Texas. The inset shows a normalized tracing of the Georgetown reflection and its ghost. All consistent lineups on the records at all shot depths from 30 to 200 feet were picked. These picks were corrected to a surface datum and plotted against shot depth as shown on Figure 7. The same distinction between reflections and ghosts made in Figure 4 can be made here.

The shooting and plotting procedure described above is a good test for determination of the degree of ghost interference present in any given area. These tests have been made by crews working in a large number of areas under a wide variety of shooting conditions. The results of all such tests showed the presence

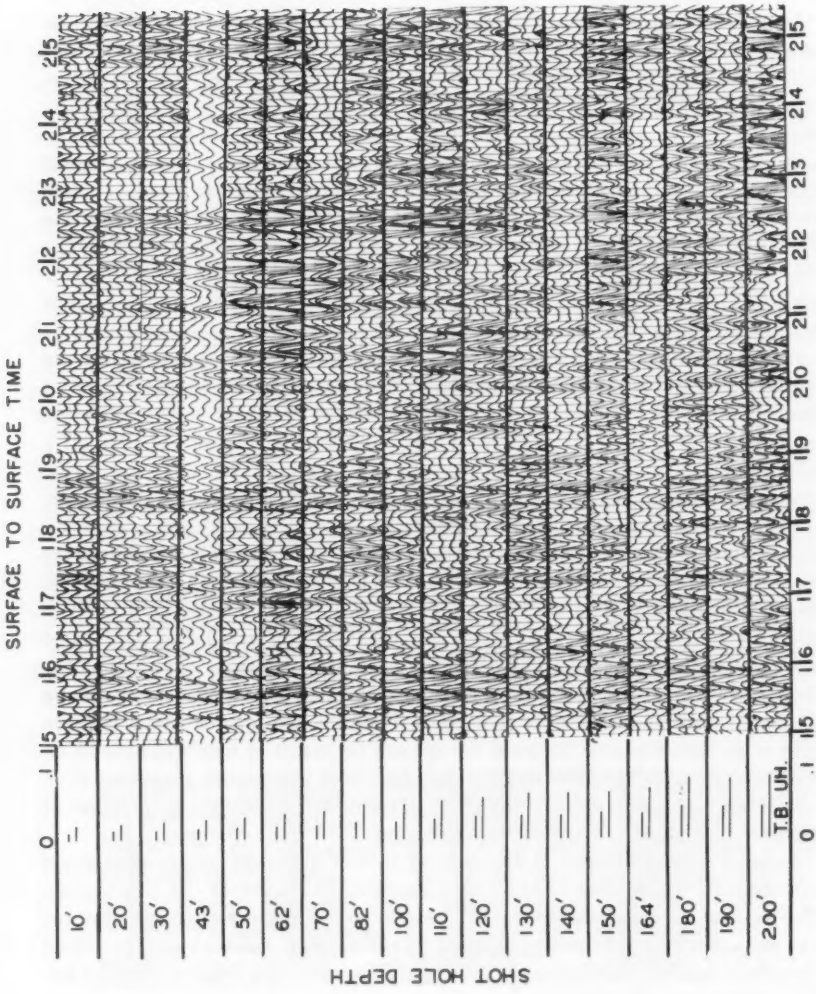

FIG. 2. Records taken at one location in the South Louisiana Gulf Coast Area showing the change of record character with hole depth. The effect of ghosting shows as a hole variable.

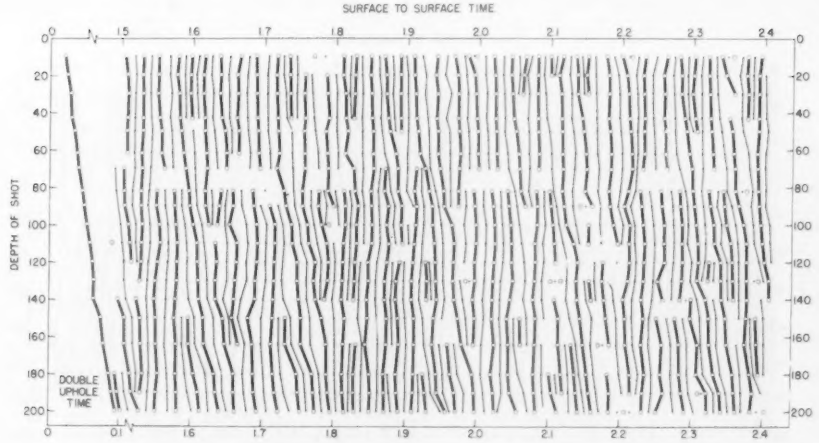

FIG. 3. A detailed plot of trough and peak times from the records in Figure 2. The multiplicity of reflections and ghosts make identification and accurate recording of either event very difficult.

of some ghost interference. It is therefore felt that all interpreters should consider carefully how much their work has been influenced by meaningless ghosts.

THEORY

The basis for the design and operation of vertically distributed charges was taken from studies of acoustical radiating theory and line microphone theory (Olson, 1947). This same theory has been used to explain the action of horizontal

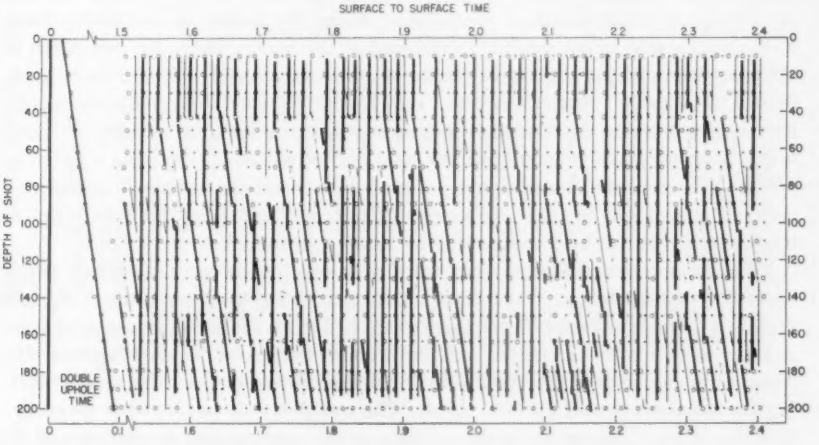

FIG. 4. A generalized plot of Figure 3 showing an attempt to separate some reflection and ghost events. Ghosts parallel double uphole time.

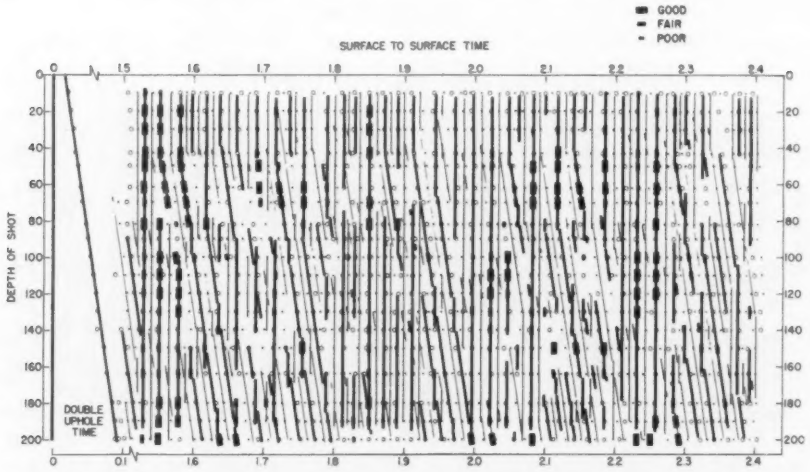

FIG. 5. A plot showing the relative quality of events plotted in Figures 3 and 4 indicating that many of the good lineups are actually ghosts.

pattern shots (Daly, 1956). Figure 8 is a polar plot of sensitivity versus angle of sound incidence for nonoverdelayed line microphones and is taken from Olson. Figure 9 is a plot of the same quantities for line microphones overdelayed by one-fourth of the undelayed sound transit time through the line. Both figures show either the change in directivity of a given microphone with frequency or the change in directivity with length of microphone for a given frequency. A comparison of the figures shows that directivity increases with overdelay for the same frequency and length of microphone. Using the theory of reciprocity these deductions apply to the sending (shot) end of the energy path. An indication of the magnitude of the theoretical value of overdelay can be deduced from these figures in terms of practical values. From Figure 8 a good directional characteristic is given by a distributed source 4 wavelengths long. A velocity of 7,000 feet per second and a frequency of 40 cycles per second would require a source 700 feet long. In contrast, from Figure 9 a good directional characteristic is given by an overdelayed source only two wavelengths or 350 feet long. The loss in downward amplitude can be compensated by using a stronger source.

The two preceding figures were based on a continuous wave, such as a single tone. The applicability of the theory outlined above to discontinuous signals, such as a "Ricker wavelet," is demonstrated in Figure 10. The directional characteristics shown were calculated for continuous charges, or wavelet sources, distributed in the vertical direction over the distance traversed by the wavelet during its apparent period (White, 1958). The overdelay d_0 employed is given by: $d_0=(V_m/V_d)-1$, where V_m is the velocity of the surrounding formation and V_d is the average delayed detonation velocity of the elongated charge.

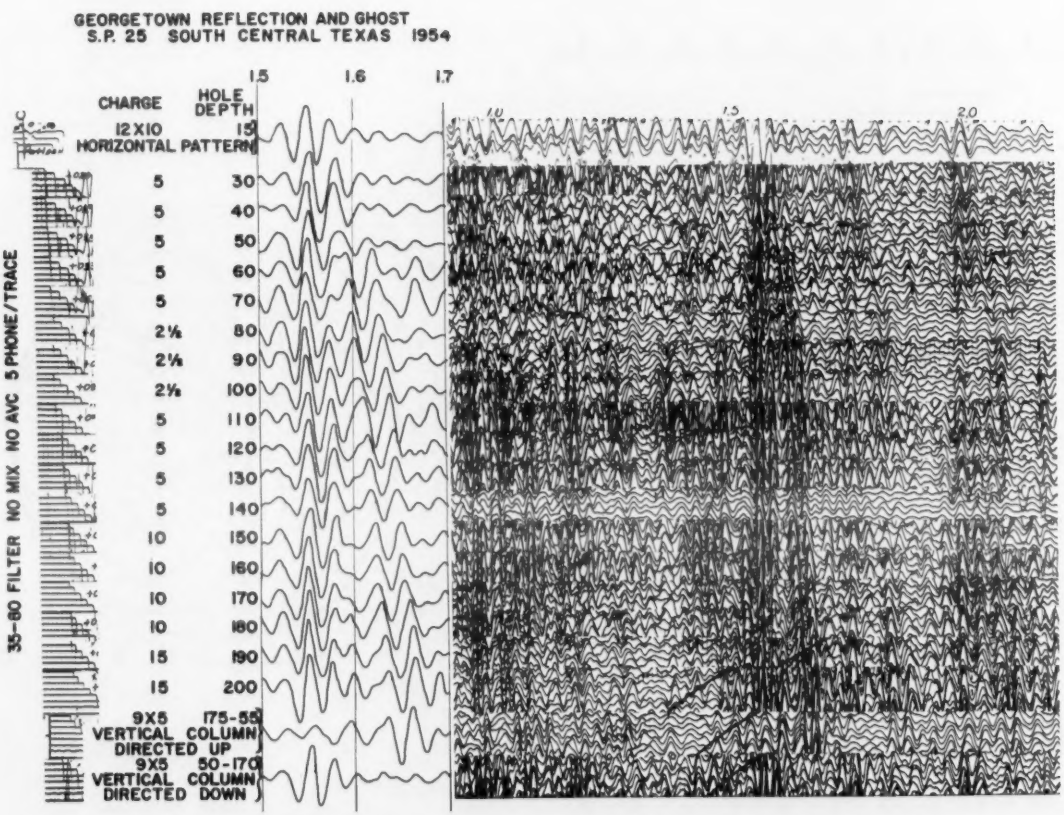

FIG. 6. Records taken at one location in South Central Texas showing the change of reflection character with shot depth and charge array. The inset shows the Georgetown reflection and its ghost.

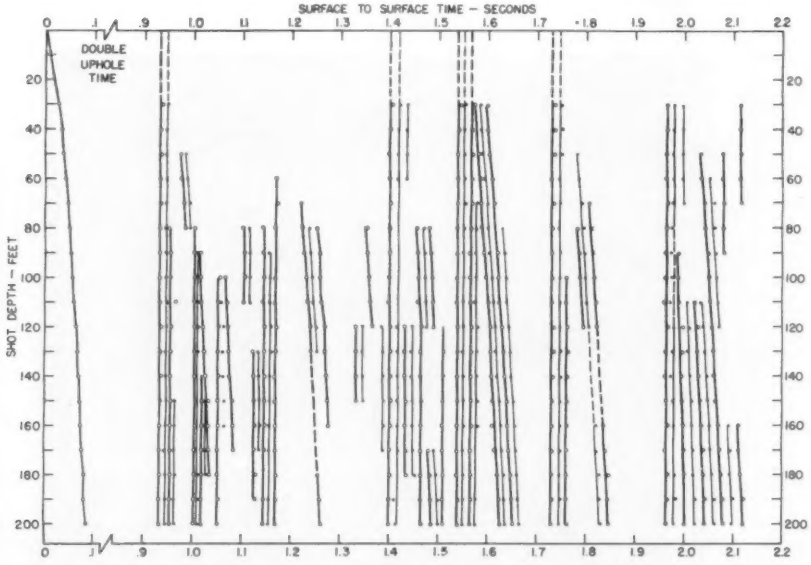

FIG. 7. A plot of the events on the records shown in Figure 6 showing that changes in ghost reflection times are directly proportional to changes in twice the uphole time.

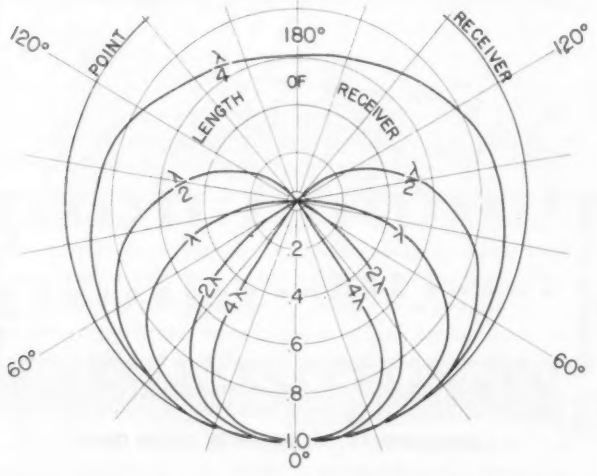

FIG. 8. Polar plot of the directivity of a non-overdelayed line microphone as calculated by Olson for a continuous signal.

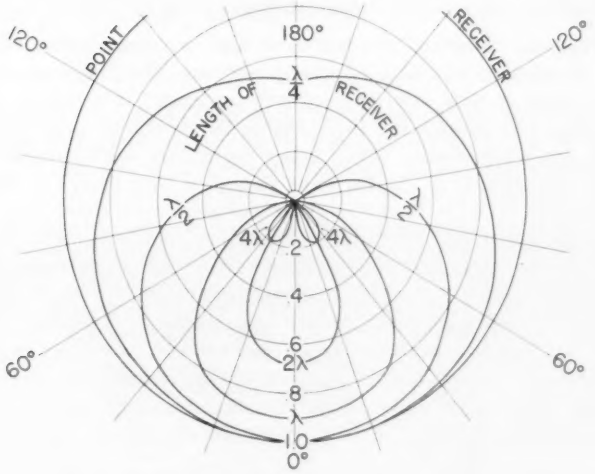

FIG. 9. Polar plot of the directivity of a ¼th overdelayed line microphone as calculated by Olson for a continuous signal.

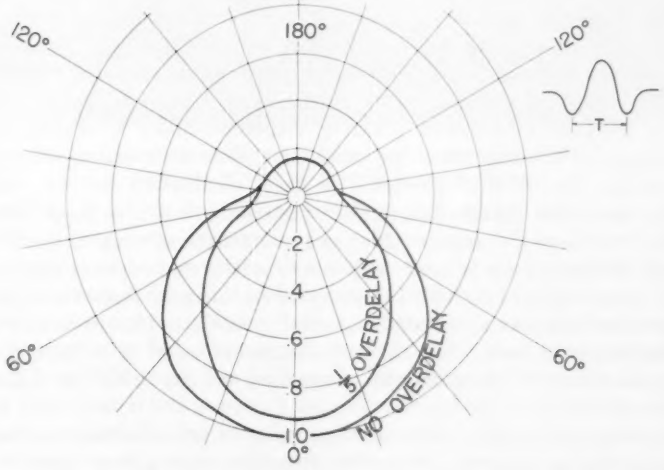

FIG. 10. Polar plot of the directivity of non-overdelayed and ¼th overdelayed column charges calculated for a Ricker wavelet. The length of the column charges is equal to the apparent wavelength of the wavelet.

DESCRIPTION

Two types of elongated charges were used to demonstrate the effect of vertically distributed and delayed energy sources. The first type consisted of separate charges of high velocity explosive suspended in a column by a rope. The explosion was propagated from charge to charge by primacord through primacord delay connectors. These delay connectors were obtained from the Explosives Department of the Du Pont Company with delays of about one or two milliseconds. The Du Pont Company designation for connectors with these two delay times is MS-1 and MS-2 respectively.

The design of this spaced charge type of elongated charge was controlled by the degree of directivity required at a frequency contained in the seismic spectrum. This design frequency was usually taken as the inverse of the longest peak to peak time appearing on a seismogram taken in the area in which the charges were to be used. The velocity of detonation was controlled by charge spacing, s, the delay time, t_d, of available primacord connectors, and the velocity of detonation, V_r, of the primacord and dynamite. Charge spacing was calculated by

$$s = \frac{V_p V_m t_d}{V_p(1 + d_0) - V_m}$$

Total length of the elongated charge was usually limited by the cost of drilling shot-holes and the difficulties and hazards involved in making up this type of charge. The length was approximated by $L = KV_m/f$, where K is a directivity factor proportional to the degree of directivity required, and f is the design frequency discussed above. The exact length was then found by $L = Ns$ where N is a whole integer equal to the number of delay connectors used. Experimentation with charges of various lengths and the same V_d indicated that a value of $K = \frac{1}{2}$ is adequate to eliminate ghosting. Experimentation at several locations with charges of different velocities found the optimum amount of over-delay to be about $\frac{1}{4}$. The effect of overdelay on ghost elimination was not visible on records taken with charges longer than $\frac{1}{2}$ wavelength of the design frequency ($K = \frac{1}{2}$). Overdelayed charges as short as $\frac{1}{4}$ wavelength attenuated ghosting that was still visible on records taken with non-overdelayed charges of this length.

The second type of elongated charge used in this work is shown in Figure 11 and consisted of a continuous column of small cartridges of low velocity explosive in a flexible plastic tube. This columnar charge was found to be very superior to the spaced elongated charge in ease of handling and dependability of operation. It is manufactured by the Hercules Powder Company and is designated by them as the EP-172 series of explosives. These columns are obtainable in lengths of approximately 92 feet with detonation velocities ranging from 6,500 to 13,500 feet per second under 50 psi of water pressure. Additional information can be obtained from Hercules in the form of a booklet entitled "A Suggested Field

Procedure for Handling, Loading, and Priming Hercules EP-172 Seismograph Explosives."

EFFECT OF DIRECTIVITY IN THE HORIZONTAL PLANE

An example of the ability of elongated charges to radiate more initial energy in the direction of propagation than in the lateral direction is shown in Figure 12. The two records shown in this figure were taken with identical instrument settings and spreads. Formation velocity was 7,000 feet per second below the weathered

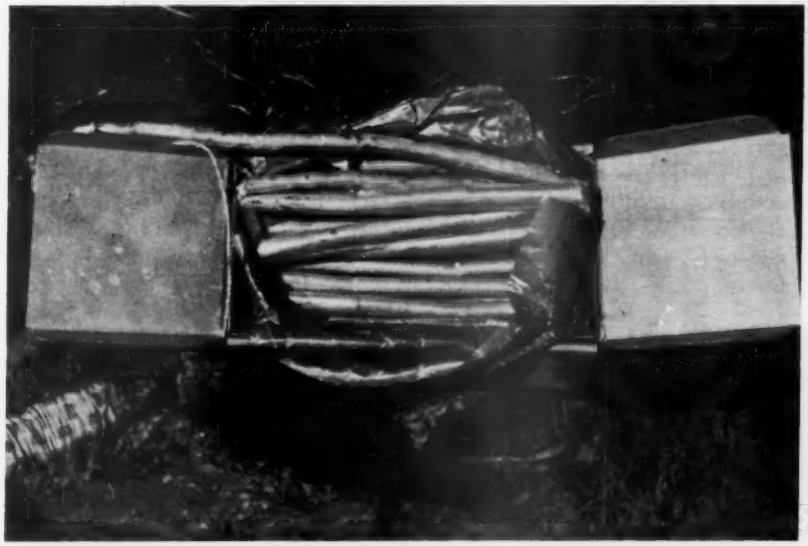

FIG. 11. An elongated charge developed from this experimental study and manufactured by the Hercules Powder Company.

layer. The velocity of detonation of the elongated charge was 5,600 feet per second. Measurements from similar points on the two records show that the ratio of the amplitude of the first incident horizontal signal to the downward signal on the elongated charge record is about one-seventh of that on the point charge record. This is a measure of the performance of the charge independent of the imperfect medium in which it is placed. If noise is derived from horizontally radiated energy in the reflection spectrum, the directivity of the charge is invaluable.

It has been illustrated in the literature that shallow horizontal patterns are a highly directive energy source. Experience has shown that single columns of EP-172 in single deep holes are equal to 36 hole patterns in noise-reducing ability where conditions are equally favorable to both. The consistency with which re-

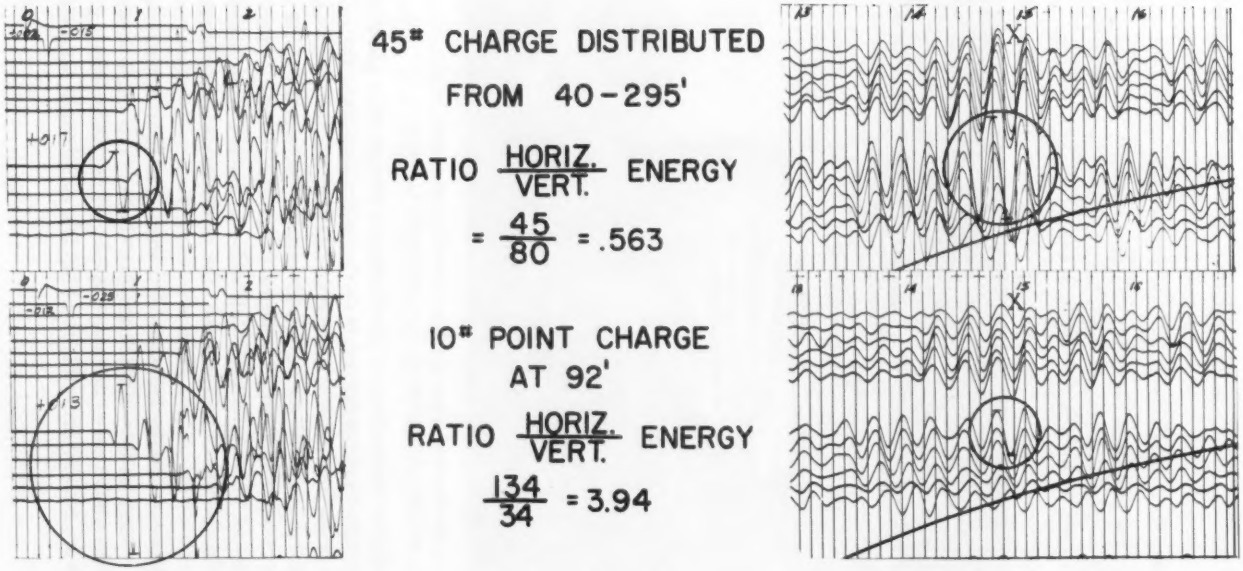

FIG. 12. Records showing the directional characteristics of a column charge as compared to a point charge at a location in North Central Texas. Ratios are calculated using amplitudes of first breaks and a reflection later on the record. This shows an increase of 7 to 1 in vertical energy over the essentially horizontal first break energy.

flection character is maintained by columns is also equal to that of patterns under these conditions.

EFFECT OF DIRECTIVITY IN THE VERTICAL DIRECTION

Elongated charges are able to radiate more initial energy downward than upward. This high "front to back ratio" eliminates ghosting. It has been stated (Hawkins, 1956) that ghosting is probably the most important shot hole variable. The authors of this paper heartily concur.

Figure 13 shows the results from an elongated charge detonated upward compared to one detonated downward. The first record shows nearly all ghosts while the second record shows none. This fact was established by retracing the ghost record with each trace inverted and shifting the retraced record to the left about twice the uphole time. The results of this operation are shown on the bottom record of this figure. The correlation with the un-ghosted record is very good. Figure 14 is a better example of the ability of an elongated charge to produce only ghosts, or completely eliminate them, when its direction of detonation is reversed. The traces shown as solid lines were traced from a record taken with downward detonation. The traces shown as dashed lines were inverted and corrected for time delay after they were traced from a record taken with upward detonation.

The directivity of the elongated charges can separate wanted and unwanted events on records taken with single charges of high velocity powder. This effect is illustrated in Figure 15 which shows the same trace copied from three records taken at the same location. The trace from the single charge is shown to be the summation of the column charge traces. This effect can also be seen on the bottom three records of Figure 6.

CONCLUSIONS

Examination of the top records of Figure 6 and times plotted for depths less than 50 feet on Figure 4 indicates that shallow shot depths are a possible solution to the ghost problem. The existence of thick weathering and high noise levels associated with shots in the weathering limits the application of this solution. The use of shallow pattern holes, however, has proved a solution to ghosting and other problems in many areas. The advisability of using either patterns or columns in marginal data country should be decided on the basis of comparative data quality only. In areas where shot-hole drilling is not difficult, economic considerations will favor the use of columns since they are easily adaptable to field operations. A crew working in South Central Texas was consistently able to shoot over 250 holes per month while using elongated charges. Another operational advantage is that permits can often be obtained in places where patterns would not be allowed. On the debit side, columns are not desirable in areas where data quality is highly sensitive to changes in shot depth. The benefits of columns are lost if they cannot be loaded in an interval in the borehole in which the surrounding formations have reasonably consistent acoustic properties.

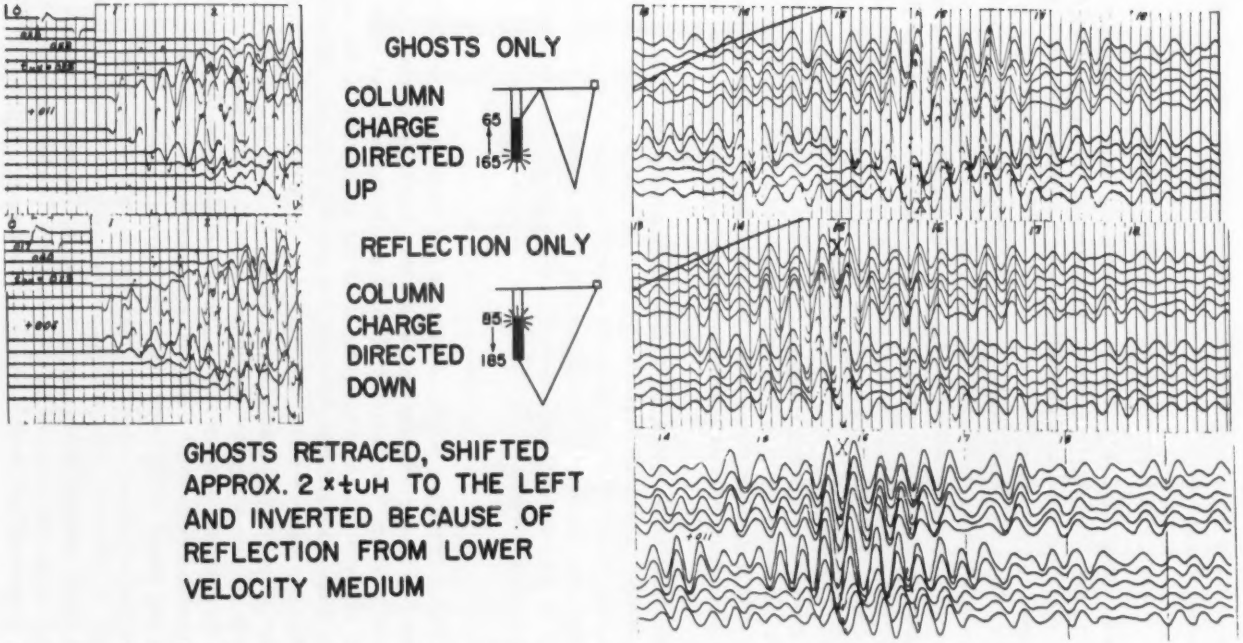

FIG. 13. Records showing the directional characteristics of column charges in the vertical direction by comparing upward and downward detonations.

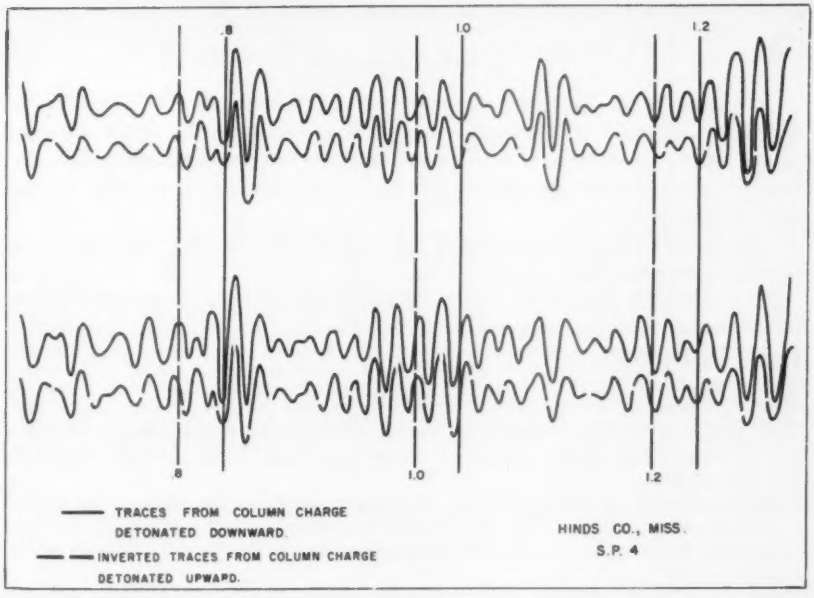

FIG. 14. Comparison of the center traces from two records taken at the same location after the traces from the charge detonated upward were inverted and shifted left by approximately twice the uphole time.

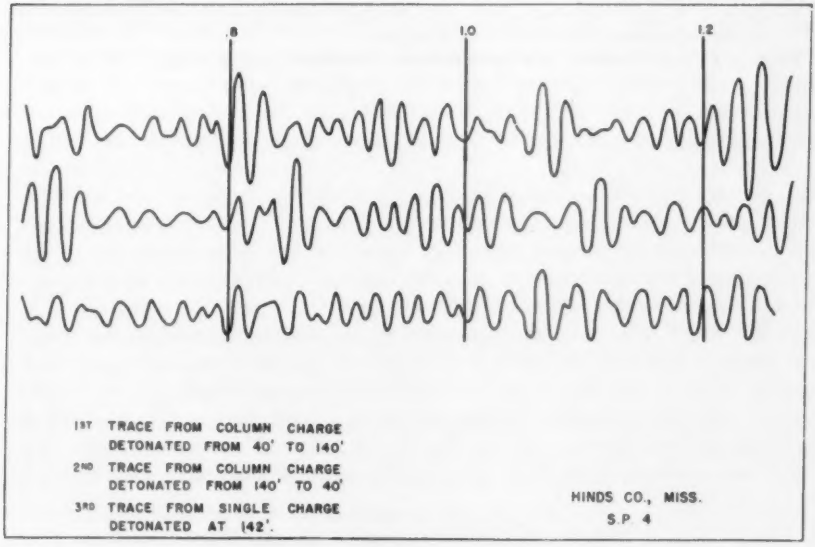
.8
1.0
1.2
1ST TRACE FROM COLUMN CHARGE DETONATED FROM 40' TO 140'
2ND TRACE FROM COLUMN CHARGE DETONATED FROM 140' TO 40'
3RD TRACE FROM SINGLE CHARGE DETONATED AT 142'.
HINDS CO., MISS.
S.P. 4

FIG. 15. Comparison of the same trace copied from three records taken at the same location showing the delay of the charge directed up and the summation of the up and the down charges by a point charge.

ACKNOWLEDGMENTS

The authors of this paper express their appreciation to the Magnolia Petroleum Company for allowing them to present this material. Space does not permit listing all those of that company who worked on this project, but Mr. James C. Eley and Mr. George W. Isensee must be singled out for their invaluable contributions.

Primacord delay connectors made by the Du Pont Company aided materially in this experimentation.

The columnar explosive in the form now being used was developed through the Hercules Powder Company with the cooperation, help, and guidance of Dr. R. W. Lawrence.

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GEOPHYSICS, VOL. XXIII, NO. 1 (JANUARY, 1958), PP. 97–127, 8 FIGS.

FREQUENCY ANALYSIS FOR GRAVITY AND MAGNETIC INTERPRETATION*

WILLIAM C. DEAN†

ABSTRACT

The operations of second derivative, analytic continuation, smoothing, the removing of residuals or regionals, and others in gravity and magnetic interpretation are analogous mathematically to the filtering action of electric circuits. The main difference between the two is that electrical filters act on functions of one variable (time), whereas the geophysical filters must act on functions of the two space variables (x and y). This paper develops linear filter theory for gravity and magnetic interpretation. As an application of the theory, downward continuation is discussed in some detail. The frequency response of upward continuation is an exponential function decreasing with increasing frequency. The inverse process of downward continuation has a frequency response which is the reciprocal of the upward continuation response. This paper discusses a method of matching frequency responses by coefficient sets and shows by examples some of the inherent difficulties in downward continuation. A final example calculated analytically shows how good a downward continuation can be expected from a finite coefficient set.

PART I—THEORETICAL DEVELOPMENT AND APPLICATIONS

INTRODUCTION

We distort almost all of our geophysical data in certain desirable ways. For operations on gravity and magnetic data, we use analytic continuations, second derivative, and smoothing to suppress some characteristics of the data and emphasize others not too evident on the original map. The mathematics governing most of the operations on gravity and magnetic data is identical to that which describes the behavior of electric filter circuits. The distorting effects of coefficient sets on gravity and magnetic space data are exactly analogous to that of a time domain filter on seismograms (Jones, Morrison, Sarrafian, Spieker, 1955; Simpson, 1955; Swartz, Sokoloff, 1954; Wadsworth, Robinson, Bryan, Hurley, 1953). In one case the frequencies are measured in cycles per unit length; in the other, in cycles per unit time.

There are several advantages to exploiting frequency analysis in gravity and magnetic interpretation. First, since the mathematics is the same, we can make use of the entire body of filter theory literature. Second, we may be able to apply a more direct approach for the evaluation of operations such as smoothing or continuation. We can even avoid complicated details such as the solution of many simultaneous equations for determining coefficient sets. Third, we can make quantitative evaluations of the effects of sampling grids and different coefficient sets without resorting to empirical tests on actual data. Fourth, we will find frequency analysis helpful in evaluating unwanted effects such as data errors. The biggest advantage, however, may be the added insight gained from another point of view. The equations describing these geophysical problems are often

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much simpler when expressed in frequency terms. Consequently, the entire result of an operation or a modification of an operation can often be visualized without any detailed calculations.

Other writers, e.g., Nettleton (1954), have mentioned the filtering effects of operations on gravity and magnetic data. Swartz (1954) made use of the Fourier integral and the Fourier series approach with the frequency representation of data. Bullard and Cooper (1948) developed a Fourier series approach to downward continuation. Tomoda and Aki (1955) developed a filter theory method for digital downward continuations which obviated computing the Fourier series of the gravity data. Spatial frequency analysis is currently being used extensively in optics (O'Neill, 1956). This paper stresses the input-output filter behavior of gravity and magnetic interpretation from the electric circuit theory point of view. As a practical application of the theory, a detailed study of downward continuation is presented showing the troubles that arise, the reasons for them, and how good a continuation we can expect to get.

LINEAR FILTER ANALOGY FOR GEOPHYSICAL INTERPRETATION

If an electric circuit analogy for magnetic and gravity interpretation exists, the mathematics describing both systems are similar. We must show that the magnetic and gravity data processing operations we employ, or could employ, are equivalent to filtering operations. To do this, let us first describe the behavior of filter circuits.[1]

The input to a filter and its output are voltages which vary in time. The input, $\mathcal{E}_i(t)$, to a linear filter and its output, $\mathcal{E}_0(t)$, are related by the following integral equation known as a convolution:

$$\mathcal{E}_0(t) = \int_{-\infty}^{\infty} \mathcal{E}_i(t - \tau) W(\tau) d\tau. \tag{1}$$

The function $W(t)$, to which we shall refer as the weighting function, is a characteristic of the filter. It is actually the response of the filter to an impulse.

The input and output time functions can also be thought of as functions of frequency. If the input is a sinusoidal voltage, it is already expressed as a function of frequency; namely, the frequency of the sine wave. If the time function were repetitive, we could express it as an infinite (Fourier) series of sines and cosines; that is, in terms of the fundamental frequency and its harmonics. If the function were not repetitive, we would use the Fourier integral rather than the Fourier series representation. Then all frequencies would be present instead of only a fundamental and its integral harmonics. The general relations which express a function of time, $\mathcal{E}(t)$, as a function of frequency, $E(\omega)$, are the Fourier trans-

[1] There are many books available on filter theory. For example, see the second chapter of a book by James, Nichols, Phillips (1947) or the development in Part II of this paper.

forms,

$$E(\omega) = \int_{-\infty}^{\infty} \mathcal{E}(t) e^{-i\omega t} dt$$

$$\mathcal{E}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(\omega) e^{+i\omega t} d\omega, \quad i = \sqrt{-1} \tag{2}$$

where $\omega/2\pi$ is the frequency in cycles per unit time.

The Fourier transform of the convolution integral equation (1) results in a simplified input-output equation in terms of the frequency variable, ω.

$$E_0(\omega) = E_i(\omega) Y(\omega). \tag{3}$$

The functions $E_0(\omega)$, $E_i(\omega)$, and $Y(\omega)$ are the Fourier transforms of $\mathcal{E}_0(t)$, $\mathcal{E}_i(t)$, and $W(t)$ respectively. The fact that the input-output equation in terms of frequency is so simple is the main reason frequency analysis is useful. For example, seismic traces are time functions but we often think of them as functions of frequency. The seismic shots give rise to low-frequency noise, such as ground roll and high-frequency energy, neither of which penetrate the earth sufficiently to be useful in defining deep reflections. Consequently, seismic filter responses, $Y(\omega)$, are small for these frequencies but large for the reflection frequency band in between.

A time domain filter or a delay line filter (Jones, Morrison, Sarrafian, Spieker, 1955) is an analog computer that simulates the action of a filter by approximating the convolution integral equation (1). The approximation of one type of time domain filter is the following summation:

$$\mathcal{E}_0(t) \cong \sum_n W(n\Delta T)\mathcal{E}_i(t - n\Delta T)\Delta T \tag{4}$$

where the smooth variable τ has been replaced by the discrete variable $n\Delta T$. This digitalized convolution is exactly the same type of operation as that of applying a coefficient set to a profile of gravity or magnetic data. Since we use coefficient sets to approximate almost any operation on gravity and magnetic data, these operations are convolutions. Any convolution equation reduces to the simple algebraic input-output equation (3) under Fourier transformation; so frequency analysis applies to gravity and magnetic interpretation techniques just as it does to electric circuits.

We can extend the theory to include functions (inputs, outputs, and filter responses) of two or even more variables. As we might expect, we must define two frequency variables to represent a function of two independent space variables. The two-variable Fourier transforms are

$$E(u, v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathcal{E}(x, y) e^{-i(ux+vy)} dx dy,$$

$$\mathcal{E}(x, y) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(u, v) e^{+i(ux+vy)} du dv. \tag{5}$$

The two-variable convolution integral is

$$\mathcal{E}_0(x, y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathcal{E}_i(x - \alpha, y - \beta)W(\alpha, \beta)d\alpha d\beta \tag{6}$$

and the two-variable input-output frequency equation is

$$E_0(u, v) = E_i(u, v)\,Y(u, v) \tag{7}$$

where $u/2\pi$ and $v/2\pi$ are the frequencies in cycles per unit length in the x and y directions respectively.

We could say much more about the properties of linear filters in general and geophysical filtering operations in particular. For the most part we will leave such discussions as well as the mathematical derivations to Part II. Here we only want to outline the theory and illustrate its application on an example problem.

DOWNWARD CONTINUATION

Since we do much of our data processing by numerical methods utilizing coefficient sets, let us consider the problem of finding the coefficient set which approximates a given operation and find how good the approximation is. There are several reasons why analytic continuation is an excellent problem to demonstrate the linear filter theory approach. First, the operation and its frequency response are fairly easy to specify exactly. Second, analytical test problems are easy to devise and calculate. Finally, the operation is inherently so unstable that limitations and any existing errors in the theory, the application of the theory, or the data show up immediately. Our procedure will be to find first the theoretical frequency response of the filter that continuation represents. Then we must choose the coefficients so that their frequency response approximates the theoretical response.

When we have the theoretical operation in convolution form, equation (6), we can express it in frequency terms by Fourier transforms, equation (7). Continuation away from the source is defined in just this form by the well-known Dirichlet integral (Peters, 1949).

$$H(x, y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{h/2\pi}{(h^2 + \alpha^2 + \beta^2)^{3/2}} \cdot F(x - \alpha, y - \beta)d\alpha d\beta \tag{8}$$

where $H(x, y) = \mathcal{E}_0(x, y)$ is the field measured on a plane a distance h above the source, and $F(x, y) = \mathcal{E}_i(x, y)$ is the field that would be measured at the source itself.

In frequency terms the input-output equation, analogous to equation (7), is

$$K(u, v) = G(u, v)\,Y_{up}(u, v) \tag{9}$$

where $K(u, v)$, $G(u, v)$ and $Y_{up}(u, v)$ are the Fourier transforms of the measured field $H(x, y)$, the source field $F(x, y)$, and the weighting function $W_{up}(x, y)$ respectively.

$$W_{up}(x, y) = \frac{h/2\pi}{(h^2 + x^2 + y^2)^{3/2}}. \tag{10}$$

Therefore, the upward continuation filter response is given by the Fourier transform of

$$Y_{up}(u, v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{h/2\pi}{(h^2 + x^2 + y^2)^{3/2}} e^{-i(ux+vy)}dxdy = e^{-h\sqrt{u^2+v^2}}. \tag{11}$$

In any filtering process we perform, the input and the filtering operation are known; the output is the result we are seeking. This is true whether the filtering is done by electric filter circuits, analog computers, or the numerical application of coefficient sets. Thus for upward continuation the known input is the source field $F(x, y)$ or $G(u, v)$ and the unknown is the field $H(x, y)$ or $K(u, v)$ above the source.

$$K(u, v) = G(u, v)e^{-h\sqrt{u^2+v^2}}. \tag{12}$$

In downward continuation the process we are interested in performing is just the reverse. Here the measured field $H(x, y)$ or $K(u, v)$ is the known input, and we wish to find the source field $F(x, y)$ or $G(u, v)$.

$$G(u, v) = K(u, v)\, Y_{down}(u, v). \tag{13}$$

But from the upward continuation equation (12) we have

$$G(u, v) = \frac{K(u, v)}{e^{-h\sqrt{u^2+v^2}}}. \tag{14}$$

Therefore, the theoretical downward continuation response must be

$$Y_{down}(u, v) = e^{+h\sqrt{u^2+v^2}}. \tag{15}$$

Herein lies an indication of why downward continuation is so difficult. The higher the frequency, the greater the amplification it receives until infinite frequencies receive infinite amplification. This divergent nature of the theoretical frequency response prevents us from obtaining a finite theoretical weighting function. Swartz (1954) has shown that the second derivative filter response is (u^2+v^2). The rising exponential response of downward continuation, however, approaches infinity with increasing frequency faster than any finite polynomial in u and v. Therefore, we might expect downward continuation to be the most difficult operation we try to approximate.

We can simplify the presentation here by considering only the one-variable case, assuming no variation of field in the y direction. The mathematics and results are analogous to the two-variable case, and the results are easier to plot.

The Dirichlet integral in one variable is

$$H(x) = \int_{-\infty}^{\infty} \frac{h/\pi}{h^2 + \alpha^2} F(x - \alpha) d\alpha. \tag{16}$$

The filter weighting function is

$$W_{up}(x) = \frac{h/\pi}{h^2 + x^2} \cdot \tag{17}$$

The frequency response for upward continuation is the Fourier transform of this weighting function, so

$$Y_{up}(u) = \int_{-\infty}^{\infty} \frac{h/\pi}{h^2 + x^2} e^{-iux} dx = e^{-h|u|} \tag{18}$$

and for downward continuation

$$Y_{down}(u) = Y_{up}^{-1}(u) = e^{+h|u|} \tag{19}$$

which is analogous to the two-variable results.

DIGITAL EFFECTS AND THEIR FREQUENCY BEHAVIOR

Although the gravity and magnetic functions our data represent are in reality smooth continuous functions, in practice we often only know these functions at the points of intersection of a square (or other shaped) grid. Similarly, coefficient sets are digital representations of smooth continuous weighting functions. We are concerned with the problem of making our digital methods approximate the smooth theoretical operations as closely as possible.

The main effect of digitalizing data is to limit the high frequency response. Consider a profile sampled at one-mile intervals. To represent a sine wave on this profile would require at least one sample every half-cycle. Therefore, the highest frequency sinusoidal component we can measure in these data would have a frequency of one-half cycle per mile. Essentially we are assuming that no frequencies higher than this are needed to represent our data adequately. We will refer to this frequency defined by the sampling rate of our data as the cutoff frequency.

If our data sampling rate is adequate, we are assuming that the frequency response of the data for frequencies higher than the cutoff frequency is negligibly small. If this is indeed true, we do not need to specify the frequency response of our coefficient sets above the cutoff frequency. The reason is that the output frequency response will be zero for all frequencies for which the input response is zero, no matter what the filter response is (equation 7). This is fortunate for it turns out that we cannot specify the frequency response of a coefficient set above the cutoff frequency. We show in Part II of this paper that the fre-

quency response of a coefficient set W_n for the convolution

$$\mathcal{E}_0(m\Delta x) = \sum_{n=-N}^{+N} W_n \mathcal{E}_i(m\Delta x - n\Delta x) \tag{20}$$

is

$$Y_c(u) = \sum_{n=-N}^{+N} W_n e^{-iun\Delta x} \tag{21}$$

where Δx is the data sampling interval. Most of the coefficient sets we use on gravity and magnetic data are symmetrical. Thus $W_n = W_{-n}$ and the frequency response become an even function also.

$$Y_c(u) = W_0 + 2\sum_{n=1}^{N} W_n \cos(un\Delta x). \tag{22}$$

This series of cosines is essentially a Fourier series. Like a Fourier series, it repeats itself with a period equal to that of the fundamental cosine component, $\cos(u\Delta x)$. The period is

$$-\frac{\pi}{\Delta x} \leq u \leq +\frac{\pi}{\Delta x}. \tag{23}$$

Thus the maximum frequency at which we can specify the frequency response of our coefficient set is $u_{max} = 2\pi f_{max} = \pi/\Delta x$, which is precisely the cutoff frequency we mentioned before. Consequently, in our downward continuation problem we make the approximation

$$e^{+h|u|} \cong W_0 + 2\sum_{n=1}^{N} W_n \cos(un\Delta x) \tag{24}$$

for only the frequency range from zero to the cutoff frequency.

In this usable range, the frequencies most essential to the reproduction of any function are those frequencies for which the frequency spectrum of the function has the largest values. The frequencies are not necessarily the ones where the filter response of a theoretical operation has its largest values. Consider a rather simple example. Suppose two adjacent zones of the basement with different vertical magnetizations have a vertical contact. A vertical magnetometer at the basement level would measure a constant field over either zone with a discontinuity at the contact. The frequency spectrum of this step function $1/iu$, has its largest values at low frequencies (see Figure 1). If the high frequency components were absent but the low frequencies accurately represented, the resulting approximation would look like a step function. Conversely, if the low frequencies were absent and the high frequencies correct, the resulting approximation would not be a recognizable step function. Most gravity and magnetic anomalies would have

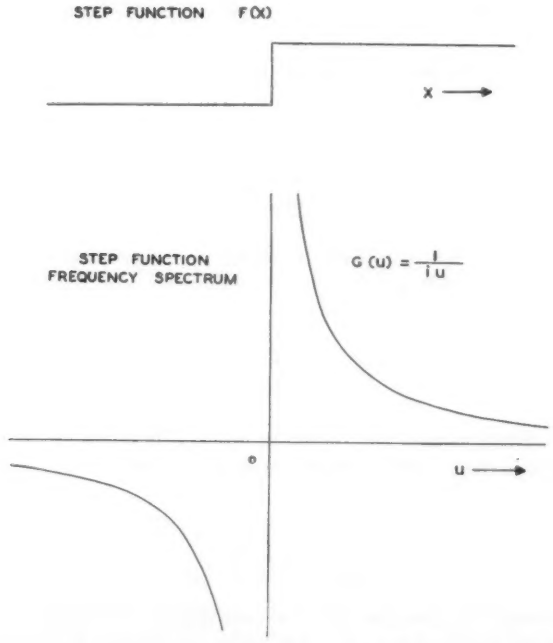

FIG. 1. The spectrum of a step function shows that its predominant frequencies are low frequencies.

predominately low frequencies even if the field were measured near the source. However, they all have some upward continuation applied by nature since measurements are appreciably above the source. This introduces another $e^{-h|u|}$ factor which again favors low frequencies. Therefore, the low frequencies are the essential ones for defining all gravity and magnetic anomalies. The high frequencies are relatively more important for the smaller, sharper anomalies and for defining sharp details.

FINDING THE COEFFICIENTS

The coefficients themselves can be found in various ways. One way is to equate the theoretical and coefficient set frequency responses, equation (24), at $N+1$ different values of frequency. Then the solution of the resulting simultaneous equations yields the coefficients, W_n. All of the coefficient sets illustrated in this paper were found by this method.

There is a much more elegant method of finding the coefficients which enables us to compute each coefficient independently of the others. This method makes use of orthogonality properties of trigonometric series and is described in Part II. Avoiding the solution of simultaneous equations is important when the number of coefficients is large.

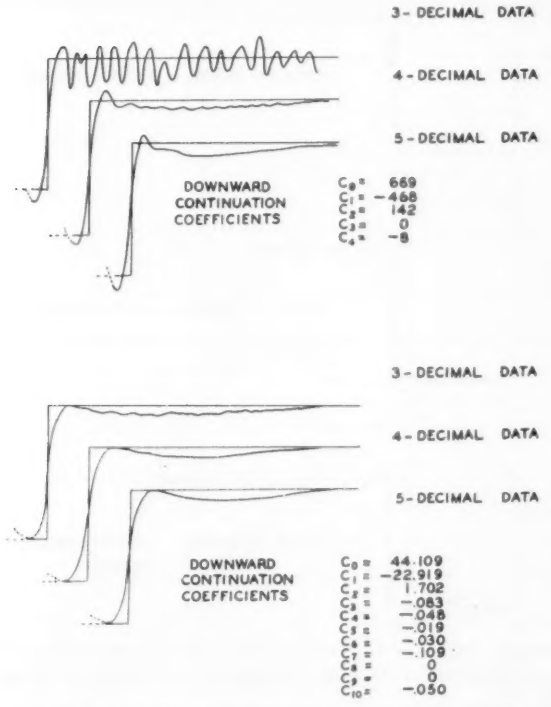

FIG. 2. The effect of the size of downward continuation coefficients and data accuracy in reproducing a step function. These coefficients are found by solving simultaneous equations and not by the use of orthogonality properties.

There are other difficulties that arise in matching the coefficient set frequency response and the theoretical frequency response. We will discuss some of these in the following examples.

MAXIMUM PERMISSIBLE COEFFICIENTS

The weighting functions of all filters which amplify high frequencies more than low frequencies (high pass filters) must be oscillatory. Consequently, downward continuation coefficients possess both positive and negative terms. Furthermore, they are not bounded by any finite number since the rising exponential filter response, $e^{+h|u|}$, is not bounded as h increases. In practice, however, our data accuracy limits the permissible size of these coefficients. Data errors are amplified by a factor of approximately twice the difference of the maximum adjacent coefficients. The curves on Figure 2 show the effect. The set with coefficients larger by a factor of ten than those of the other set requires data accurate to an extra

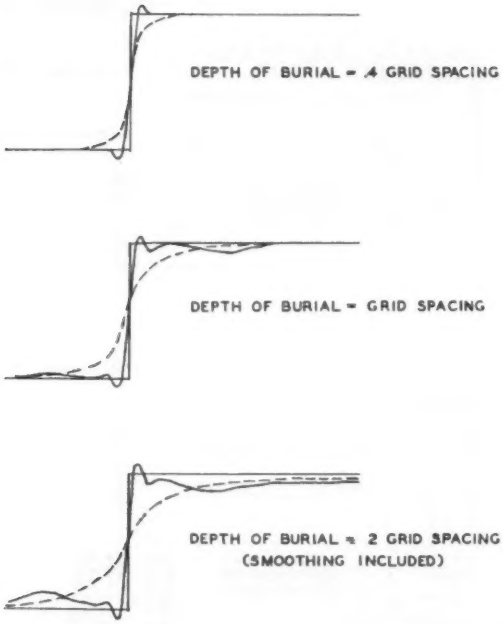

FIG. 3. Downward continuation by 17-term coefficient sets to a step function source buried at different depths. The original data are shown by the dotted curves.

decimal place to produce the same smoothness in result. This will be true for any coefficient set, but it is more pronounced for downward continuation since it is more unstable than other operations. This means that the deep anomalies must be broad ones in order for us to define them adequately by downward continuation. Figure 3 shows how the definition of a step function gets progressively worse as the depth of burial increases, and Figure 4 shows the frequency responses of the coefficient sets used.

SMOOTHING NECESSARY

The method of matching the theoretical frequency response and the coefficient set frequency response we have suggested up to now is to match them as closely as possible up to the cutoff frequency. This is not a good method. For frequencies beyond the cutoff, the two frequency responses are apt to diverge suddenly. This will always be true for high pass responses such as those of downward continuation, second derivative, or residual filters. The finite cosine series representing the coefficient set frequency response is an even function about the cutoff frequency. Consequently, if it has been rising up to the cutoff frequency, beyond this it will come down. The theoretical response, however, keeps on rising. Hence they must diverge.

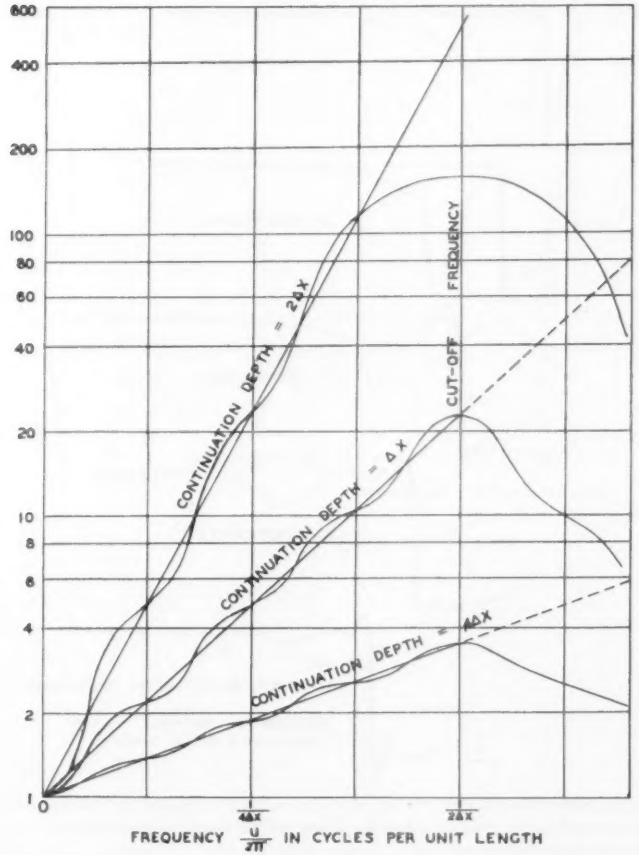

FIG. 4. Frequency responses for downward continuation coefficient sets used in step functions shown in Figure 3. The theoretical responses are shown by the dotted curves.

Since the coefficient set response must diverge from the theoretical response eventually, it is better to have them diverge gradually. In this way, distortion is deliberately introduced into the high frequency response in such a way that the all-important low frequency response of the coefficient set is more correct. Incidentally, this is exactly what we mean by smoothing. Otherwise, even with many coefficients in the series, the two responses may differ widely in the matching range, causing severe distortions in the reproduction of the source fields. Figure 5 shows the distortion of a step function that results when too few coefficients and no smoothing are used in downward continuation. In Figure 6, the normalized frequency responses of the downward continuation coefficients

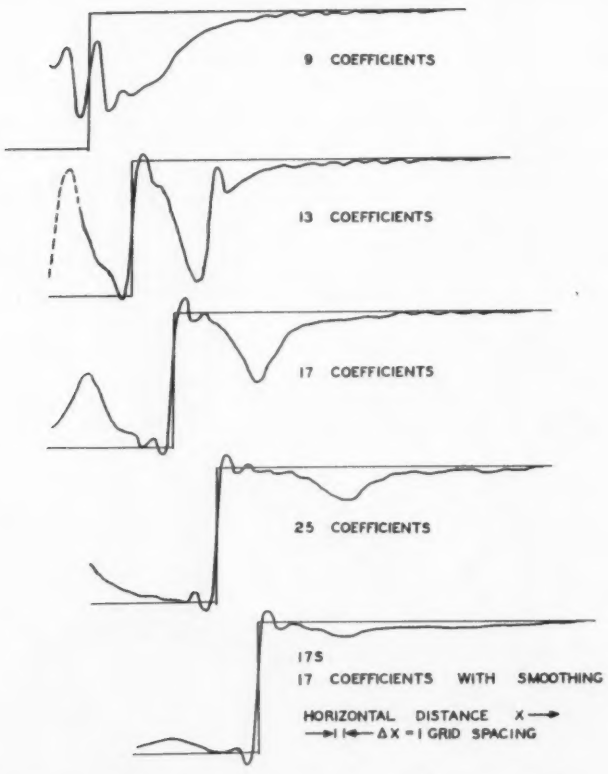

FIG. 5. Reproduction of a step function after downward continuation by several coefficient sets. The depth of burial is twice the grid spacing. These results show the improvement with increased ground coverage by coefficient sets and with smoothing.

used on the examples of Figure 5 show the frequency distortion resulting from too few coefficients and no smoothing.

ANALYTICAL EXAMPLE

In the examples of downward continuation we have shown, there are two ways in which the coefficient set and theoretical frequency responses differ. One is the complete divergence of the two above the cutoff frequency, and the other is the periodic mismatch below the cutoff frequency. We can express both of these analytically and derive the form of the best possible downward continuation we can expect from coefficient sets. We have shown that smoothing is necessary to minimize the mismatch in the pass band, and so we shall include smoothing too. What form of smoothing we use is relatively unimportant since the only differ-

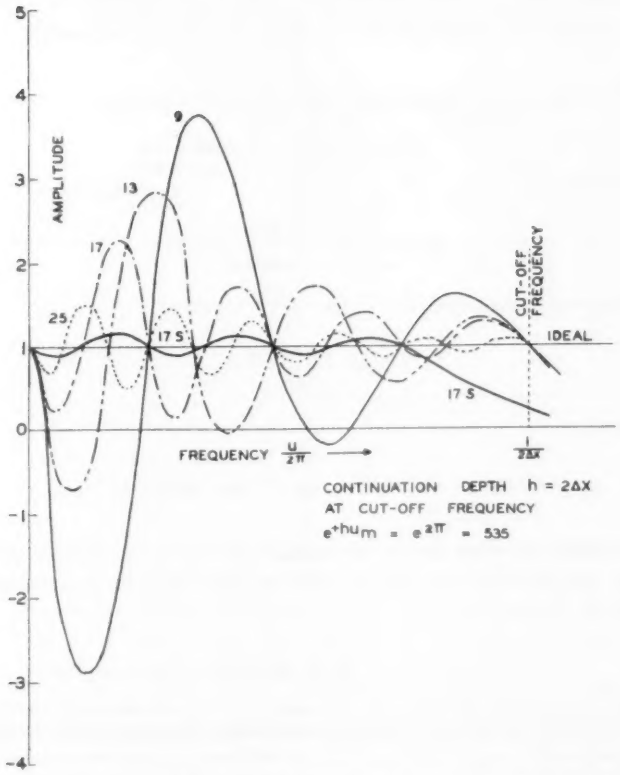

FIG. 6. Frequency responses of downward continuation sets normalized by multiplying by the true upward continuation response, $e^{-h|\omega|}$. The number designates the number of coefficients in the set and the letter "*S*" designates smoothing. The curves show that forcing a coefficient set of too few terms to fit the ideal response at high frequencies causes severe mismatch at low frequencies.

ences among various smoothing methods will be in the types of resulting overshoot for step functions. We will use normal error curve smoothing which possesses no overshoot at all since the Fourier transform of a normal error curve is a normal error curve.

Therefore, let us find the resulting step function approximation by continuing an arc tangent function by a smoothed coefficient set. The frequency response of our coefficient set will match very closely the function[2]

[2] The error between a finite trigonometric series and its matching function will nearly equal the first neglected term if the convergence is reasonably rapid (Lanczos, 1938–39). The first neglected term for our case approximates a sine rather than a cosine function since the series has been adjusted to make the error zero at zero frequency. Also, the error will be negative since at the origin the slope of a cosine series is zero and that of the rising exponential is positive.

$$e^{+h|u|-a^2u^2} - a_0 \sin(M\Delta x|u|) = c_0 + 2\sum_{n=1}^{N} c_n \cos(nu\Delta x). \tag{41}$$

Using the input-output equations in frequency form, we have

$$E_0(u) = E_i(u)\, Y_{\text{down}}(u) \tag{35}$$

where the input is

$$H(x) = \tan^{-1}\left(\frac{x}{h}\right) = \varepsilon_i(x) \tag{42}$$

and its frequency response

$$E_i(u) = \frac{1}{iu} e^{-h|u|}. \tag{43}$$

Consequently,

$$E_0(u) = \frac{1}{iu}\left[e^{-a^2u^2} - a_0 e^{-h|u|} \sin(M\Delta x|u|)\right]. \tag{44}$$

The expression in the brackets is the normalized frequency response. A property of Fourier transforms states that the effect of the $1/iu$ factor is an integration in x (Campbell, Foster, 1931).

$$\int_{-\infty}^{x} f(x)dx$$

where $f(x)$ is in this case the Fourier transform of the normalized frequency response. So

$$\begin{aligned}\varepsilon_0(x) &= \int_{-\infty}^{x} dx\left[e^{-x^2/4a^2} - a_0\left(\frac{M\Delta x - x}{h^2 + (M\Delta x - x)^2} + \frac{M\Delta x + x}{h^2 + (M\Delta x + x)^2}\right)\right] \\ &= \frac{\pi}{2}\left[1 + \operatorname{erf}\left(\frac{x}{2a}\right)\right] - \frac{a_0}{2}\log\frac{h^2 + (M\Delta x + x)^2}{h^2 + (M\Delta x - x)^2}\end{aligned} \tag{45}$$

where

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt.$$

This approximate step function appears in Figure 7. The high-frequency response is limited by the data accuracy as we have discussed before. Its effect is to round the corners in the vicinity of the step function discontinuity. The periodic mismatch at low frequencies gives rise to a false anomaly apparently buried an additional depth h with a half width, $M\Delta x$, equal to the half width of the down-

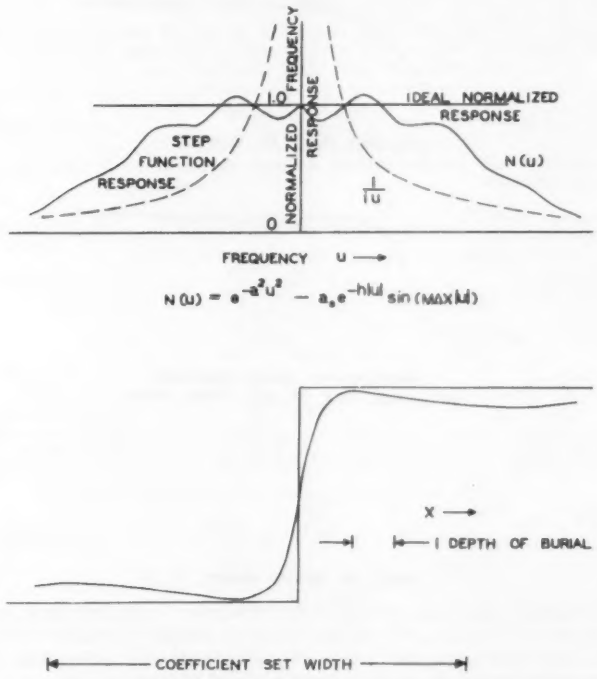

FIG. 7. These curves show the two inaccuracies prevalent in downward continuation coefficients. The finite slope at the discontinuity is due to limited high-frequency response. This effect is unavoidable if coefficients are to remain reasonably small. The improper asymptotic behavior on the flanks is due to the coefficient set having finite ground coverage.

ward continuation coefficient set used. This type of false anomaly is apparent on the flanks of any of the continuation examples shown in this paper. This is the most serious fault of downward continuations by coefficient sets since a new anomaly is created for every anomaly processed. Elimination of this effect requires greater area coverage by the coefficient set.

$$\lim_{M\to\infty}\left[\frac{a_0}{2}\log\frac{h^2+(M\Delta x+x)^2}{h^2+(M\Delta x-x)^2}\right]=0 \tag{46}$$

and

$$\lim_{M\to\infty} a_0 = 0.$$

The convergence toward zero, however, is slow. With a ratio of coefficient set coverage to continuation depth of 16 to 1 (second example, Figure 3), the false

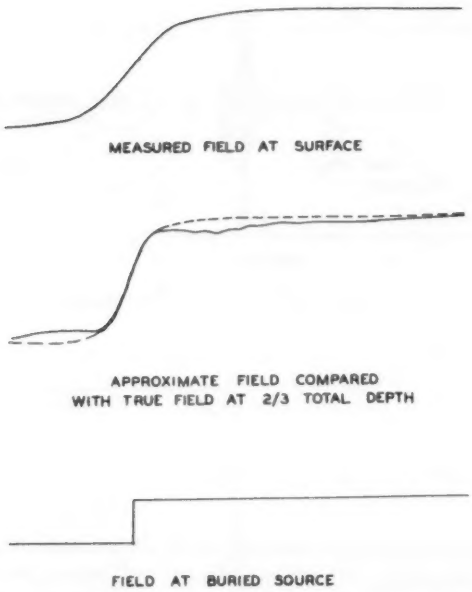

FIG. 8. This figure shows that the downward continuation to 2/3 total depth by a smoothed 17-term coefficient set reproduces the field very well in the vicinity of the discontinuity and poorer on the flanks. Downward continuation used to a fraction of total depth can separate discontinuities from adjacent anomalies and the remaining depth estimated by other methods.

anomaly is about 11 percent of the main one. When this width-to-depth ratio is 40 to 1, the false anomaly is less than two percent (first example, Figure 3). Since infinite edge effects such as these may not be practical, the "best possible" continuation will probably produce results of the form shown in Figure 7. The false anomalies are all at twice the depth of continuation. Perhaps they can be recognized from this characteristic and disregarded, but where the data are complicated by many conflicting anomalies, the interpretation may be difficult and lead to false depth estimates. Downward continuation will separate conflicting anomalies partially at least. As shown by Figure 8, slopes in the vicinity of discontinuities are still quite accurate when continued to two-thirds the total depth of burial. The remaining depth might be estimated in various ways (Peters, 1949).

We can apply linear filter theory to other geophysical operations following the methods we used for downward continuation. A table of some theoretical geophysical operations, their weighting functions, and their frequency responses for both one and two variables is shown in Table I. Some of these operations, such as smoothing, are not defined by any exact frequency response. What form

TABLE I

THE THEORETICAL FILTER WEIGHTING FUNCTIONS AND FREQUENCY RESPONSES FOR SOME GEOPHYSICAL DATA OPERATIONS FOR BOTH THE ONE AND TWO VARIABLES ARE TABULATED HERE FOR COMPARISON

Geophysical Operation	Weighting Function $W(x)$ and $W(x, y)$	Frequency Response $V(u)$ and $V(u, v)$
Smoothing and other low pass filters	Weighting function mostly positive values	Low frequencies favored over high frequencies
Regional removal and other high pass filters	Damped oscillatory function	High frequencies favored over low frequencies
Second derivative	$\frac{\partial^2}{\partial z^2} = -\frac{\partial^2}{\partial x^2}$	u^2
	$\frac{\partial^2}{\partial z^2} = -\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)$	u^2+v^2
Derivative-integral operations of any order (Negative orders of derivatives imply integrals.)	$\sum_m a_m \frac{d^m}{dx^m}$	$\sum_m a_m (iu)^m$
	$\sum_m \sum_n a_{mn} \frac{\partial^{m+n}}{\partial x^m \partial y^n}$	$\sum_m \sum_n a_{mn} (iu)^m (iv)^n$
Upward continuation	$\frac{h/\pi}{h^2+x^2}$	$e^{-h\lvert u\rvert}$
	$\frac{h/2\pi}{(h^2+x^2+y^2)^{3/2}}$	$e^{-h\sqrt{u^2+v^2}}$
Downward continuation	$\lim_{u_0 \to \infty} \left[\frac{h/\pi}{h^2+x^2} e^{hu_0} \left(\cos u_0 x + \frac{x}{h} \sin u_0 x\right)\right]$	$e^{+h\lvert u\rvert}$
	$\lim_{\rho_0 \to \infty} \left[\frac{1}{2\pi} \int_0^{\rho_0} e^{+h\rho} \rho J_0(\rho\sqrt{x^2+y^2}) d\rho\right]$	$e^{+h\sqrt{u^2+v^2}} = e^{+h\rho}$

the filter operation takes depends upon the problem at hand. The list in Table I is for illustrative purposes and does not pretend to exhaust the possibilities.

PART II—MATHEMATICAL DETAILS

FILTER THEORY

There are several ways to express the input-output relations of a filter. In this section we will discuss three: the differential equation, the algebraic frequency equation, and the convolution integral. We will indicate how the first arises and derive the other two from it. In circuit equations we can express the voltage, V, across a circuit element (whether inductance, L, resistance, R, or capacitance, C)

in terms of the current through the element, I:

$$V_L = L\frac{dI}{dt}$$

$$V_R = RI \tag{47}$$

$$V_C = \frac{1}{C}\int I dt.$$

In a linear circuit these are the only circuit elements that exist. Consequently, no matter how complicated the circuit is, the input and output voltages can always be related by a differential equation with constant coefficients.

$$a_m\frac{d^m\mathcal{E}_0}{dt^m} + a_{m-1}\frac{d^{m-1}\mathcal{E}_0}{dt^{m-1}} + \cdots + a_1\frac{d\mathcal{E}_0}{dt} + a_0\mathcal{E}_0 =$$

$$b_n\frac{d^n\mathcal{E}_i}{dt^n} + b_{n-1}\frac{d^{n-1}\mathcal{E}_i}{dt^{n-1}} + \cdots + b_1\frac{d\mathcal{E}_i}{dt} + b_0\mathcal{E}_i. \tag{48}$$

The coefficients (a's and b's) depend upon the R, L, and C comprising the circuit and so are constants. By differentiating both sides of the input-output equation repeatedly, any integrals due to capacitor voltages can be removed with the result in the form of equation (48).

We can convert equation (48) into an algebraic equation by the use of Fourier transforms.

$$E(\omega) = \int_{-\infty}^{\infty}\mathcal{E}(t)e^{-i\omega t}dt$$

$$\mathcal{E}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}E(\omega)e^{+i\omega t}d\omega, \qquad i = \sqrt{-1}. \tag{2}$$

With the definitions in equation (2) we can find the Fourier transform of $d\mathcal{E}/dt$ with a uv substitution.

$$\int_{-\infty}^{\infty}\frac{d\mathcal{E}}{dt}e^{-i\omega t}dt = \left[\mathcal{E}(t)e^{-i\omega t}\Big|_{-\infty}^{\infty}\right] + \int_{-\infty}^{\infty}\mathcal{E}(t)i\omega e^{-i\omega t}dt. \tag{49}$$

With $\mathcal{E}(\infty)=\mathcal{E}(-\infty)=0$ we have

$$\int_{-\infty}^{\infty}\frac{d\mathcal{E}}{dt}e^{-i\omega t}dt = i\omega E(\omega). \tag{50}$$

Applying this method repeatedly gives the Fourier transform of the nth derivative.

$$\int_{-\infty}^{\infty} \frac{d^n \mathcal{E}}{dt^n} e^{-i\omega t} dt = (i\omega)^n E(\omega).$$

Substituting this result to equation (48) gives us

$$[a_m(i\omega)^m + a_{m-1}(i\omega)^{m-1} + \cdots + a_1 i\omega + a_0]E_0(\omega) = [b_n(i\omega)^n + b_{n-1}(i\omega)^{n-1} + \cdots + b_1 i\omega + b_0]E_i(\omega) \quad (51)$$

or

$$E_0(\omega) = \frac{\sum_{k=0}^{n} b_k(i\omega)^k}{\sum_{k=0}^{m} a_k(i\omega)^k} E_i(\omega) = Y(\omega)E_i(\omega) \quad (3)$$

which is an algebraic input-output equation in terms of the frequency variable.

The third form of the input-output equation results from applying the inverse Fourier transform to equation (3) as follows:

$$\frac{1}{2\pi}\int_{-\infty}^{\infty} E_0(\omega)e^{+i\omega t}d\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} E_i(\omega)\,Y(\omega)e^{+i\omega t}d\omega. \quad (52)$$

The left side of the equation is by definition $\mathcal{E}_0(t)$. In the right side of the equation we substitute the Fourier transform of the weighting function, $W(t)$, for $Y(\omega)$. That is,

$$Y(\omega) = \int_{-\infty}^{\infty} W(\tau)e^{-i\omega\tau}d\tau \quad (53)$$

so equation (52) becomes

$$\mathcal{E}_0(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E_i(\omega)e^{+i\omega t}d\omega \int_{-\infty}^{\infty} W(\tau)e^{-i\omega\tau}d\tau. \quad (54)$$

Inverting the order of integration, we get

$$\mathcal{E}_0(t) = \int_{-\infty}^{\infty} W(\tau)d\tau\left[\frac{1}{2\pi}\int_{-\infty}^{\infty} E_i(\omega)e^{+i\omega(t-\tau)}d\omega\right].$$

Now the integral in the brackets is by definition $\mathcal{E}_i(t-\tau)$, so the resulting equation becomes the convolution integral:

$$\mathcal{E}_0(t) = \int_{-\infty}^{\infty} \mathcal{E}_i(t-\tau)W(\tau)d\tau. \quad (1)$$

The fact that the Fourier transform of the product of two functions is the con-

volution of the transforms of the functions is known as Parseval's theorem, a fundamental theorem of transform calculus.

There are three main properties of linear filters. The first is superposition: the output of the filter to a sum of inputs is equal to the sum of the outputs of the filter with each input applied separately. That is, if for each input $f_n(t)$ the output of the filter is $F_n(t)$, for the input $\sum_n a_n f_n(t)$ the output will be the sum $\sum_n a_n F_n(t)$. The second property states that the filter behavior is independent of time origin. That is, if $F(t)$ is the response of the filter to an input $f(t)$, then $F(t-t_0)$ will be the response of the filter to the input $f(t-t_0)$. The third property states that the o tput of a filter depends only on the present and past values of the input, which merely means that a filter does not respond to an input before that input is applied.

In the case of gravity and magnetic interpretation, the independent variable is space, x, or the two space variables, x and y. Two of the three properties of linear filters hold. The first, superposition, holds since the effect of two anomalous sources can be analyzed as the effect of each separately, added together. The second, independence of the choice of data origin, holds since the operations we are discussing are applied in the same manner over an entire area. The third property, the filter response depending only on present and past values of the input, does not hold since the independent variables are space, not time. Thus the outputs of gravity and magnetic interpretation operations can and do depend on any and all values of the input data. This difference between space and time filters does not restrict the application of filter theory to space systems. Quite the contrary. It actually removes a restriction of time filters, permitting greater versatility in the space filters.

The equations in the two variables x and y which are analogous to the differential circuit equation (48) are partial differential equations.

$$\sum_{m,n} a_{mn} \frac{\partial^{m+n} \mathcal{E}_0}{\partial x^m \partial y^n} = \sum_{p,q} b_{pq} \frac{\partial^{p+q} \mathcal{E}_i}{\partial x^p \partial y^q} . \tag{55}$$

Laplace's equation, or the second derivative operation, provides a good example.

$$\frac{\partial^2 \mathcal{E}_i}{\partial x^2} + \frac{\partial^2 \mathcal{E}_i}{\partial y^2} = -\frac{\partial^2 \mathcal{E}_i}{\partial z^2} = \mathcal{E}_0(x, y). \tag{56}$$

The application of the two-variable Fourier transforms (equation 5) in the same manner as the single-variable case (equations 49, 50, and 51) leads to the two-variable input-output frequency equation.

$$E_0(u, v) = E_i(u, v) \frac{\sum_{p,q} b_{pq}(iu)^p (iv)^q}{\sum_{m,n} a_{mn}(iu)^m (iv)^n} = E_i(u, v) Y(u, v). \tag{7}$$

Application of the two-variable Fourier transform to this equation is analogous to the steps of equations 52, 53, and 54 and results in the two-variable convolution integral (equation 6). Thus any gravity or magnetic operation that can be described by a constant coefficient partial differential equation or by the two-variable convolution integral can be described by the simple algebraic input-output equation in frequency.

CIRCULAR SYMMETRY OF SOME GEOPHYSICAL OPERATIONS

Since the output of a space filter can depend on any and all values of space input, we can assign any frequency response we like to a filter as long as its Fourier transform (filter weighting function) is a real function. As a practical consideration, we will usually want filter weighting functions to be symmetrical (zero phase shift filters) so that the asymmetries and trends in the output are properties of the magnetic or gravity data and not dependent upon the kind of filter we used. When the filtering effect is the same in all directions, the filter weighting function is a function of a radius variable only.

$$W(x, y) = W(\sqrt{x^2 + y^2}) = W(r). \tag{57}$$

In this case the filter frequency response $Y(u, v)$ will be a function of only a radial frequency variable $Y(\sqrt{u^2+v^2}) = Y(\rho)$. To show that this is true, we start with the normal Fourier transform,

$$Y(u, v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(\sqrt{x^2 + y^2})e^{-i(ux+vy)}dxdy. \tag{58}$$

Now we substitute polar coordinates for the rectangular:

$$\begin{aligned} x &= r\cos\theta \qquad u = \rho\cos\phi \qquad r = \sqrt{x^2 + v^2} \\ y &= r\sin\theta \qquad v = \rho\sin\phi \qquad \rho = \sqrt{u^2 + v^2} \end{aligned}$$

and get

$$\begin{aligned} Y(\rho, \phi) &= \int_0^{\infty}\int_0^{2\pi} W(r)e^{-i\rho r(\cos\theta\cos\phi+\sin\theta\sin\phi)}rdrd\theta \\ &= \int_0^{\infty} rW(r)dr\int_0^{2\pi} e^{-i\rho r\cos(\theta-\phi)}d\theta. \end{aligned}$$

But the integral[3]

$$\int_0^{2\pi} e^{+iz\cos\varphi}d\varphi = 2\pi J_0(z)$$

[3] See any text on Bessel functions.

so

$$Y(\rho, \phi) = 2\pi \int_0^\infty rW(r)J_0(\rho r)dr = Y(\rho). \tag{59}$$

Since the filter frequency response is not a function of the angle ϕ, it possesses circular symmetry whenever the weighting function does. By a similar development we can find the inverse transform and write the transform pair as

$$\begin{aligned} Y(\rho) &= 2\pi \int_0^\infty rW(r)J_0(\rho r)dr, \\ W(r) &= \frac{1}{2\pi} \int_0^\infty \rho Y(\rho)J_0(\rho r)d\rho. \end{aligned} \tag{60}$$

These relations are known as zero order Hankel transforms. The normal (one-variable) Fourier transforms can be written as Hankel transforms also with orders $\frac{1}{2}$ and $-\frac{1}{2}$.

We can make use of the rotational property of geophysical filters to calculate their Fourier direct or inverse transforms in another way. Sometimes this way is easier. Consider the direct transform in cartesian coordinates.

$$Y(u, v) = \int_{-\infty}^\infty \int_{-\infty}^\infty W(x, y)e^{-i(ux+vy)}dxdy. \tag{58}$$

We know a priori that both $W(x, y)$ and $Y(u, v)$ possess circular symmetry. Thus we can calculate the filter response along one direction and know that it will be the same for any direction. We have

$$Y(u, v) = \int_{-\infty}^\infty e^{-iux}dx \int_{-\infty}^\infty W(x, y)e^{-ivy}dy.$$

For the direction where $v=0$, we have

$$Y(u, 0) = \int_{-\infty}^\infty e^{-iux}dx \int_{-\infty}^\infty W(x, y)dy.$$

If we substitute

$$Q(x) = \int_{-\infty}^\infty W(x, y)dy \tag{61}$$

we have reduced the double Fourier transform to a single Fourier transform,

$$Y(u, 0) = \int_{-\infty}^\infty Q(x)e^{-iux}dx. \tag{62}$$

Now we can replace u by the radius variable ρ since the frequency response in the u direction is the same as in any other direction. This principle can be used to

reduce area weighting functions to profile weighting functions when there is no variation of the data in the y direction.

DERIVATION OF COEFFICIENT SETS

Let us consider now the derivation by frequency methods of the digital weighting functions used in numerical convolutions. Although we often desire our weighting functions to possess circular symmetry, this is not possible in minute detail when the weighting functions are in digital form on a square (x, y) grid. We may approximate circular symmetry reasonably well by using many coefficients in a set. However, detailed circular symmetry is not sufficiently satisfied to justify using the polar variables $r=\sqrt{x^2+y^2}$ and $\rho=\sqrt{u^2+v^2}$ described in the preceding section. Consequently, we will use the Cartesian coordinate system for all coefficient set analysis.

In order to derive the frequency response of a coefficient set, let us first start with a very simple case, the coefficient which has a constant value at the origin and zero everywhere else. Such a set, of course, is trivial since the output map would be exactly the constant times the original data. Since the input and output are identical, a convolution with such a set is equivalent to a filter which attenuates no frequency relative to any other. Therefore, the frequency response must be a constant and, in this case, equal to the constant amplification factor. If we call this coefficient set or weighting function $W_0(x, y)$ where

$$W_0(x, y)\begin{cases}\neq 0 & \text{for } x = y = 0^4\\ = 0 & \text{for } x \neq 0 \text{ or } y \neq 0 \text{ or both}\end{cases} \tag{63}$$

then its frequency response is given by the Fourier transform which we have already stated is the constant, k.

$$Y_0(u, v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W_0(x, y)e^{-i(ux+vy)}dxdy = k. \tag{64}$$

Suppose we define a function $f(x, y)$ with a Fourier transform $g(u, v)$.

$$g(u, v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x, y)e^{-i(ux+vy)}dxdy.$$

Let us find the effect on the frequency response of shifting the $f(x, y)$ function to $f(x-x_0, y-y_0)$. The trick is to multiply by $e^{+i(ux_0+vy_0)}e^{-i(ux_0+vy_0)}=1$.

$$\begin{aligned}&\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x - x_0, y - y_0)e^{-i(ux+vy)}dxdy\\ &\quad = e^{-i(ux_0+vy_0)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x - x_0, y - y_0)e^{-i[u(x-x_0)+v(y-y_0)]}dxdy\\ &\quad = e^{-i(ux_0+vy_0)}g(u, v).\end{aligned} \tag{65}$$

[4] Actually, $W_0(x, y)$ is the Dirac delta function, $k\delta(x, y)$.

Therefore, the frequency response of a single coefficient, k, located at (x_0, y_0) is $ke^{i(ux_0+vy_0)}$. By extending this argument to many points, the frequency response of a general coefficient set c_{mn} is

$$Y_c(u, v) = \sum_m \sum_n c_{mn} e^{-i(um\Delta x+vn\Delta y)} \tag{66}$$

where Δx and Δy are the sampling intervals in and x and y directions. In the single-variable case we have

$$Y_c(u) = \sum_m c_m e^{-ium\Delta x}. \tag{67}$$

This development is well known and can be found in many texts on linear filter theory.

ORTHOGONAL SERIES RELATIONS

The formulas we have just derived enable us to compute directly the frequency response of any known coefficient set. We are often interested, however, in calculating the coefficients of a set which approximates a certain theoretical operation. In this case the frequency response is known and the coefficients are unknown. As we mentioned in Part I, one way to do this is to equate the theoretical frequency response and the coefficient set frequency response for several different frequencies, obtaining a set of simultaneous equations from which the unknown coefficients can be found. However, we would like to avoid the laborious process of solving simultaneous equations and solve for the coefficients directly. This we can do if the series is orthogonal. Series of sines and cosines can be made orthogonal if the series is either infinite, which is simply the Fourier series, or finite.

Any function can be represented by the sum of an even function and an odd function. Consequently, no loss of generality results if we treat the even and odd cases separately.

The orthogonal trigonometric series are as follows: If $g(u)$ is an odd function, the series has only sine terms,

$$g(u) = 2 \sum_{m=1}^{M} b_m \sin um\Delta x \tag{68}$$

and the coefficients, b_p, are given by

$$b_p = \frac{1}{M} \sum_{k=1}^{M} g(k\Delta u) \sin \frac{kp\pi}{M} \tag{69}$$

where the smooth variable x has been replaced by $m\Delta x$, the variable u by $k\Delta u$, and where $M\Delta u = \pi/\Delta x$, the cutoff frequency we defined in Part I.

If $g(u)$ is an even function, a cosine series results,

$$g(u) = a_0 + 2\sum_{m=1}^{M-1} a_m \cos um\Delta x + a_M \cos uM\Delta x \tag{70}$$

and the coefficients, a_p, are given by

$$a_p = \frac{1}{M}\left[\frac{1}{2}\, g(0) + \sum_{k=1}^{M-1} g(k\Delta u) \cos\frac{kp\pi}{M} + \frac{1}{2}\, g(M\Delta u)\cos p\pi\right]. \tag{71}$$

The half-weights on the first and last terms are necessary to make the series orthogonal.

The two-variable sine series is

$$g(u, v) = 4\sum_{m=1}^{M}\sum_{n=1}^{M} b_{mn} \sin(um\Delta x) \sin(vn\Delta y) \tag{72}$$

with the coefficients given by

$$b_{pq} = \frac{1}{M^2}\sum_{k=1}^{M}\sum_{l=1}^{M} g(k\Delta u, l\Delta v) \sin\frac{kp\pi}{M} \sin\frac{lq\pi}{M} \tag{73}$$

and $\Delta u\Delta x = \Delta v\Delta y = \pi/M$.

The two-variable cosine series is

$$\begin{aligned} g(u, v) = {} & a_{00} + 2\sum_{m=1}^{M-1} a_{m0} \cos(um\Delta x) + a_{M0} \cos(uM\Delta x) \\ & + 2\sum_{n=1}^{M-1} a_{0n} \cos(vn\Delta y) + 4\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} a_{mn} \cos(um\Delta x) \cos(vn\Delta y) \\ & + 2\sum_{n=1}^{M-1} a_{Mn} \cos(uM\Delta x) \cos(vn\Delta y) + a_{0M} \cos(vM\Delta y) \\ & + 2\sum_{m=1}^{M-1} a_{mM} \cos(um\Delta x) \cos(vM\Delta y) + a_{MM} \cos(uM\Delta x) \cos(vM\Delta y) \end{aligned} \tag{74}$$

and the coefficients are found by a similar series,

$$\begin{aligned} a_{pq} = \frac{1}{M^2}\Bigg[& \frac{1}{2}\left(\frac{1}{2}\, g(0, 0) + \sum_{k=1}^{M-1} g(k\Delta u, 0) \cos\frac{kp\pi}{M} + \frac{1}{2}\, g(M\Delta u, 0) \cos p\pi\right) \\ & + \sum_{l=1}^{M-1} \cos\frac{lq\pi}{M}\left(\frac{1}{2}\, g(0, l\Delta v) + \sum_{k=1}^{M-1} g(k\Delta u, l\Delta v) \cos\frac{kp\pi}{M}\right. \\ & \qquad \left. + \frac{1}{2}\, g(M\Delta u, l\Delta v) \cos p\pi\right) \\ & + \frac{1}{2}\cos q\pi\left(\frac{1}{2}\, g(0, M\Delta v) + \sum_{k=1}^{M-1} g(k\Delta u, M\Delta v) \cos\frac{kp\pi}{M}\right. \\ & \qquad \left. + \frac{1}{2}\, g(M\Delta u, M\Delta v) \cos p\pi\right)\Bigg]. \end{aligned} \tag{75}$$

SUBSIDIARY TRIGONOMETRIC RELATIONS

In order to prove orthogonality of these series, we will need a few trigonometric relations. For convenience we will list the ones to which we will refer here. They are:

$$\sum_{k=1}^{n} \cos k\theta = \frac{\cos\left(\frac{n+1}{2}\theta\right)\sin\frac{n\theta}{2}}{\sin\frac{\theta}{2}} \tag{76}$$

and from (76) we have

$$\sum_{k=1}^{M-1} \cos\frac{km\pi}{M} = \frac{\cos\frac{M}{2}\frac{m\pi}{M}\sin\frac{(M-1)m\pi}{2M}}{\sin\frac{m\pi}{2M}}$$

$$= \frac{\cos\frac{m\pi}{2}}{\sin\frac{m\pi}{2M}}\left(\sin\frac{m\pi}{2}\cos\frac{m\pi}{2M} - \cos\frac{m\pi}{2}\sin\frac{m\pi}{2M}\right) \tag{77}$$

$$= -\cos^2\frac{m\pi}{2M} = -\frac{1}{2}(1+\cos m\pi) = -\frac{1}{2}(1+(-1)^m)$$

$$= \begin{cases} 0 & \text{if } m \text{ is an odd integer} \\ -1 & \text{if } m \text{ is an even integer and} \\ M-1 & \text{if } m = 0 \end{cases}$$

since if $m=0$,

$$\sum_{k=1}^{M-1} \cos\frac{km\pi}{M} = \sum_{k=1}^{M-1} (+1)^k = M-1.$$

Now making use of equation (77), we have

$$\frac{1}{2} + \sum_{k=1}^{M-1} \cos\frac{pk\pi}{M} + \frac{1}{2}\cos p\pi = \begin{cases} \frac{1}{2}+0+\frac{1}{2}(-1)^p = 0 & \text{if } p \text{ is odd,} \\ \frac{1}{2}-1+\frac{1}{2}(-1)^p = 0 & \text{if } p \text{ is even, } p \neq 0 \\ \frac{1}{2}+(M-1)+\frac{1}{2} = M & \text{if } p = 0. \end{cases} \tag{78}$$

In a similar manner,

$$\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\cos\frac{km\pi}{M}+\frac{1}{2}\cos m\pi\cos p\pi$$

$$=\frac{1}{2}\left\{1+\sum_{k=1}^{M-1}\left[\cos\frac{k\pi}{M}(p-m)+\cos\frac{k\pi}{M}(p+m)\right]\right.$$

$$\left.+\frac{1}{2}\cos(p-m)\pi+\frac{1}{2}\cos(p+m)\pi\right\}$$

$$=\frac{1}{2}\left\{\left(\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{k\pi}{M}(p-m)+\frac{1}{2}\cos(p-m)\pi\right)\right.$$

$$\left.+\left(\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{k\pi}{M}(p+m)+\frac{1}{2}\cos(p+m)\pi\right)\right\}.$$

Now by use of equation (78) the first of these terms is zero for all p's except when $p-m=0$. The second term is always zero since p and m are positive integers and so $p+m\neq 0$. Thus we have

$$\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\cos\frac{km\pi}{M}+\frac{1}{2}\cos p\pi\cos m\pi=\begin{cases}0 & \text{if } p\neq m\\ \dfrac{M}{2} & \text{if } p=m<M.\end{cases}\tag{79}$$

The same method applies to this expression:

$$\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\cos k\pi+\frac{1}{2}\cos p\pi\cos M\pi$$

$$=\frac{1}{2}\left[1+\sum_{k=1}^{M-1}\cos\frac{k\pi}{M}(M-p)+\cos\frac{k\pi}{M}(M+p)\right.$$

$$\left.+\frac{1}{2}\cos(M-p)\pi+\frac{1}{2}\cos(M+p)\pi\right]$$

$$=\frac{1}{2}\left[\left(\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{k\pi}{M}(M-p)+\frac{1}{2}\cos\pi(M-p)\right)\right.$$

$$\left.+\left(\frac{1}{2}+\sum_{k=1}^{M-1}\cos\frac{k\pi}{M}(M+p)+\cos\pi(M+p)\right)\right].$$

The first of these terms is zero unless $p=M$ by equation (78). In the second

term, we can write the cosine terms as

$$\cos\frac{k\pi}{M}(M+p) = \cos\frac{k\pi}{M}(M+p)\cos 2k\pi + \sin\frac{k\pi}{M}(M+p)\sin 2k\pi$$

$$= \cos\frac{k\pi}{M}(2M - M - p) = \cos\frac{k\pi}{M}(M-p). \tag{80}$$

Substituting this above, we have

$$\frac{1}{2} + \sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\cos k\pi + \frac{1}{2}\cos p\pi\cos M\pi = \begin{cases} 0 & \text{if } p \neq M \\ M & \text{if } p = M. \end{cases} \tag{81}$$

PROOFS OF ORTHOGONALITY

We will show here only the proof of orthogonality of the cosine series. The proof for the sine series is similar. The method is to write the cosine series, equation (70), with the discrete variable $u = k\Delta u$ and by substituting it into the equation for the coefficient c_p, show that $c_p = a_p$.

$$c_p = \frac{1}{M}\left[\frac{1}{2}g(0) + \sum_{k=1}^{M-1} g(k\Delta u)\cos\frac{kp\pi}{M} + \frac{1}{2}g(M\Delta u)\cos p\pi\right] \tag{71}$$

$$= \frac{1}{M}\left[\frac{1}{2}\left(a_0 + 2\sum_{m=1}^{M-1} a_m + a_M\right)\right.$$

$$+ \sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\left(a_0 + 2\sum_{m=1}^{M-1} a_m\cos\frac{km\pi}{M} + a_M\cos k\pi\right)$$

$$\left. + \frac{1}{2}\cos p\pi\left(a_0 + 2\sum_{m=1}^{M-1} a_m\cos m\pi + a_M\cos M\pi\right)\right]$$

$$= \frac{1}{M}\left[a_0\left(\frac{1}{2} + \sum_{k=1}^{M-1}\cos\frac{kp\pi}{M} + \frac{1}{2}\cos p\pi\right)\right.$$

$$+ 2\sum_{m=1}^{M-1} a_m\left(\frac{1}{2} + \sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\cos\frac{km\pi}{M} + \frac{1}{2}\cos p\pi\cos m\pi\right)$$

$$\left. + a_M\left(\frac{1}{2} + \sum_{k=1}^{M-1}\cos\frac{kp\pi}{M}\cos k\pi + \frac{1}{2}\cos p\pi\cos M\pi\right)\right].$$

Using equations (78), (79), and (81) in the above form, we get

$$c_p = \frac{1}{M}\left[a_0\begin{cases} 0 & \text{if } p \neq 0 \\ M & \text{if } p = 0 \end{cases} + 2\sum_{m=1}^{M-1} a_m\begin{cases} 0 & \text{if } p \neq m \\ \frac{M}{2} & \text{if } p = m \end{cases}\right.$$

$$\left. + a_M\begin{cases} 0 & \text{if } p \neq M \\ M & \text{if } p = M \end{cases}\right]$$

or $c_p = a_p$, for $0 \leq p \leq M$, showing the validity of equation (71).

The proofs of orthogonality of the two-variable series follow directly from the one-variable proofs when we resort to a special artifice.

If we define

$$g(k\Delta u, l\Delta v) = A_{kl} = A_k B_l$$

and

$$a_{mn} = a_m b_n$$

and

$$c_{pq} = c_p d_q$$

we can write the cosine series, equation (74), as

$$g(k\Delta u, l\Delta v) = A_{kl} = \left[\left(a_0 + 2\sum_{m=1}^{M-1} a_m \cos\frac{km\pi}{M} + a_M \cos k\pi\right) \cdot \left(b_0 + 2\sum_{n=1}^{M-1} b_n \cos\frac{ln\pi}{M} + b_M \cos l\pi\right)\right] \tag{82}$$

and the coefficients, equation (75), as

$$c_{pq} = c_p d_q = \left[\frac{1}{M}\left(\frac{1}{2}A_0 + \sum_{k=1}^{M-1} A_k \cos\frac{kp\pi}{M} + \frac{1}{2}A_M \cos p\pi\right) \cdot \frac{1}{M}\left(\frac{1}{2}B_0 + \sum_{l=1}^{M-1} B_l \cos\frac{lq\pi}{M} + \frac{1}{2}B_m \cos q\pi\right)\right]. \tag{83}$$

Thus the two-variable cosine series is a product of two independent one-variable cosine series, the orthogonality of each of which we have just proved. So we have

$$c_{pq} = c_p d_q = a_p b_q = a_{pq} \tag{84}$$

and the orthogonality is proved. By this same method we can prove the orthogonality of the two-variable sine series and can even extend the proof to series of any number of independent variables.

Some question may arise here as to the validity of representing one function by the product of two other functions, which is not possible in general. Actually by the operation $A_k B_l = A_{kl} = g(k\Delta u, l\Delta v)$ we arrive only at an approximation $g(u,v) \cong g_1(u) g_2(v)$ for a limited range of u and v. Direct substitution of equation (74) in equation (75) does lead to the same orthogonal results, although the details are laborious. Moreover, in carrying out this substitution the expressions for each coefficient are always separable into the product of two independent functions analogous to the method of proof we have followed (Lanczos, 1938–39).

CONCLUSIONS

Any problem which can be described by an ordinary or partial differential

equation with constant coefficients, or by a convolution integral, can also be analyzed from the filter theory point of view. Whether the independent variable is time or not is immaterial. The Fourier transform technique still reduces the differential and integral equations to algebraic frequency equations. Many of the operations performed on gravity and magnetic data are of this type and so lend themselves to frequency analysis. We may justifiably question whether filter theory is necessary, considering that we have done gravity and magnetic interpretation without it until now. Furthermore, avoiding approximations in the frequency domain eliminates the oftentimes tedious frequency transformation. On the other hand, in the synthesis of filtering operations the required frequency response and the frequency range of importance are oftentimes quite easy to specify. Conversely, finding a finite approximation to an infinitely long weighting function for a complicated operation such as convolution can be difficult. Filter theory is helpful in evaluating filter operations derived by other methods. For example, a second derivative set of coefficients may have a frequency response quite different from the ideal over the range of frequencies defined by the sampling interval of the survey. Moreover, when the coefficient set is reduced to profile sets along various radial lines, the frequency responses in these different directions may vary considerably from each other. Since the input-output equations are simpler in frequency terms, more complicated filtering processes can be visualized. Thus the frequency approach facilitates more versatility in gravity and magnetic data processing schemes.

We have discussed the digital approach using coefficient sets to a considerable extent. The orthogonal coefficient set formulae assign a coefficient to every point on a square grid within the prescribed area of the set. For the area coverage required by most of the filtering operations we consider, this completeness of the orthogonal coefficient sets makes their use impractical for anything but large-scale digital computers and perhaps even a difficult problem for them. We must emphasize, however, that the use of the filter theory is not restricted to coefficient sets. We could, for example, perform all transformations between the space and frequency domains with smooth functions analytically. This step obviates the use of the orthogonal series relations. Then we can digitalize the approximate finite weighting function we have generated. We can even treat theoretical anomalies and filter responses in analytic terms to learn the effect of special operations. In this paper the problem of predicting the best step function we could get by a downward continuation coefficient set is a case in point. Frequency analysis will not be a panacea for all magnetic and gravity interpretation problems, but it should help to provide quantitative insight into these data processing operations and what we can reasonably expect of them.

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GEOPHYSICS, VOL. XXIII, NO. 1 (JANUARY, 1958), PP. 128–133, 1 FIG.

RESPONSE OF DYKE TO OSCILLATING DIPOLE*†

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ABSTRACT

A dyke of sulfide ore may be geophysically prospected by observing its electromagnetic response to a slowly oscillating magnetic dipole source. An excellent first approximation of the fields generated is obtained by considering the idealized case of a dyke of infinite conductivity and vanishing thickness in a vacuum. Surprisingly, this idealized problem can be solved exactly in terms of a newly discovered Green's function for Laplace's equation (in three dimensions) which is simply expressed in closed form. The magnetic scalar potential and the magnetic field are given for final results.

INTRODUCTION

Recent improvements in instrumentation make it possible to prospect geophysically a dyke of sulfide ore of high electrical conductivity by observing the response of the dyke to a slowly oscillating magnetic dipole source. For low frequencies (10 to 1,000 cps) the effect of the earth in which the dyke is actually imbedded may be neglected and the earth replaced by a vacuum. When the dyke appears to be geometrically thin, which will always be the case for source and observer far from the dyke, we may approximate the dyke of sulfide ore by a dyke of infinite conductivity and vanishing thickness.

Cylindrical coordinates are chosen as indicated in Figure 1, with the z-axis taken horizontally along the edge of the dyke, the dyke running from $z \rightarrow -\infty$ to $z \rightarrow +\infty$. The angle ϕ, which may be realized in the actual space, varies between $-\pi/2$ and $3\pi/2$. The radial distance from the edge of the dyke (the z-axis) is denoted by ρ. Cartesian coordinates are chosen with the x-axis horizontal and perpendicular to the dyke, and with the y-axis parallel to the dyke and vertical, the dyke extending from $y=0$ to $y \rightarrow -\infty$.

FUNDAMENTAL EQUATIONS

Maxwell's equations for a vacuum and for time harmonic solutions with the time variation $\exp(-i\omega t)$, where ω is the angular frequency, in rationalized *mks* units may be written according to Stratton (1941) in the form:

$$\begin{aligned} &\text{I.} \quad \nabla \times \boldsymbol{E} - i\omega\mu_0 \boldsymbol{H} = 0, \qquad &&\text{III.} \quad \nabla \cdot \boldsymbol{H} = 0 \\ &\text{II.} \quad \nabla \times \boldsymbol{H} + i\omega\epsilon_0 \boldsymbol{E} = \boldsymbol{J}, \qquad &&\text{IV.} \quad \nabla \cdot \boldsymbol{E} = 0, \end{aligned} \tag{1}$$

where the symbols have their usual meaning. For the present very small frequencies we may take $\boldsymbol{E}=0$; and Maxwell's equations (1) reduce to

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}, \qquad \nabla \cdot \boldsymbol{H} = 0. \tag{2}$$

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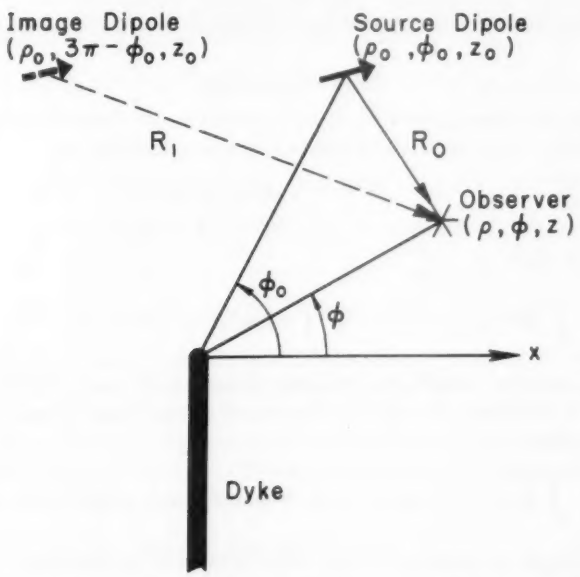

FIG. 1. Dyke of sulfide ore showing the choice of cylindrical coordinates with the z-axis taken along the edge of the dyke and perpendicular to the page. The vectors $\boldsymbol{R}_0 = \boldsymbol{r} - \boldsymbol{r}_0$ from source to observer and $\boldsymbol{R}_1$ from image to observer are also indicated.

The prescribed current distribution J for the present magnetic dipole source is

$$J = \nabla \times \boldsymbol{m}\delta(\boldsymbol{r} - \boldsymbol{r}_0), \tag{3}$$

where $\delta(\boldsymbol{r} - \boldsymbol{r}_0)$ is the Dirac delta function, $\boldsymbol{r}$ is the position vector of the observer, $\boldsymbol{r}_0$ is the position vector of the source, and $\boldsymbol{m}$ is the magnetic dipole moment. Substituting equation (3) into the first of equations (2), we obtain,

$$\boldsymbol{H} = \boldsymbol{m}\delta(\boldsymbol{r} - \boldsymbol{r}_0) - \nabla\psi, \tag{4}$$

where ψ is the scalar magnetic potential which from the second of equations (2) satisfies Poisson's equation,

$$\nabla^2\psi = \nabla \cdot \boldsymbol{m}\delta(\boldsymbol{r} - \boldsymbol{r}_0). \tag{5}$$

The boundary condition (Stratton, 1941, p. 37) requiring the normal component of the magnetic flux density to be continuous across a surface and the requirement that the magnetic field vanish inside the dyke of infinite conductivity, yields the pertinent boundary condition from equation (4),

$$\partial\psi/\partial n = 0 \quad \text{for} \quad \phi = -\pi/2, 3\pi/2, \tag{6}$$

where the derivative with respect to n means the normal derivative to the surface.

The problem is now to solve equations (5) and (6) for the geometry specified by Figure 1.

GREEN'S THEOREM

To solve equations (5) and (6) it is of interest to use Green's theorem (Morse and Feshback, 1953) for ψ and a Green's function specified by,

$$\begin{aligned} \nabla^2 G &= -4\pi\delta(\boldsymbol{r}-\boldsymbol{r}'), \\ \partial G/\partial n &= 0 \quad \text{for} \quad \phi = -\pi/2,\ 3\pi/2. \end{aligned} \tag{7}$$

Thus,

$$\int (G\nabla^2\psi - \psi\nabla^2 G)d\tau' = \int (G\partial\psi/\partial n - \psi\partial G/\partial n)da' = 0, \tag{8}$$

where the boundary conditions (6) and (7) have been used. Replacing the laplacian of ψ and G by the right hand member of equations (5) and (7), respectively, we obtain,

$$\int [G(\boldsymbol{r},\boldsymbol{r}')\nabla'\cdot\boldsymbol{m}\delta(\boldsymbol{r}'-\boldsymbol{r}_0) + 4\pi\psi(\boldsymbol{r}')\delta(\boldsymbol{r}-\boldsymbol{r}')]d\tau' = 0. \tag{9}$$

The first integral in equation (9) may be evaluated by noting that

$$\begin{aligned} \int G(\boldsymbol{r},\boldsymbol{r}')\nabla'\cdot\boldsymbol{m}\delta(\boldsymbol{r}'-\boldsymbol{r}_0)d\tau' &= -\nabla^0\cdot\boldsymbol{m}\int G(\boldsymbol{r},\boldsymbol{r}')\delta(\boldsymbol{r}'-\boldsymbol{r}_0)d\tau' \\ &= -\nabla^0\cdot\boldsymbol{m}G(\boldsymbol{r},\boldsymbol{r}_0), \end{aligned} \tag{10}$$

where the superscript zero indicates differentiation with respect to the source coordinates. Integrating the second integral in equation (9) directly and using equation (10), we obtain the solution

$$\psi(\boldsymbol{r}) = \nabla^0\cdot\boldsymbol{m}G(\boldsymbol{r},\boldsymbol{r}_0)/4\pi. \tag{11}$$

From equation (4), neglecting the case for which the source and observer are coincident, we have the desired magnetic field,

$$\boldsymbol{H} = -\nabla[\nabla^0\cdot\boldsymbol{m}G(\boldsymbol{r},\boldsymbol{r}_0)/4\pi]. \tag{12}$$

GREEN'S FUNCTION

The Green's function[1] satisfying equations (7) may be written in closed form as the sum of a source term and an image term,

$$G = G_0 + G_1, \tag{13}$$

where

$$\begin{aligned} G_0 &= (\pi + 2\tan^{-1} g_0/R_0)/2\pi R_0, \\ G_1 &= (\pi + 2\tan^{-1} g_1/R_1)/2\pi R_1, \end{aligned} \tag{14}$$

[1] The Green's function which vanishes on the surfaces $\phi = -\pi/2,\ 3\pi/2$, is given by $G = G_0 - G_1$.

where the values of the arctangent are always taken such that

$$-\pi/2 \leq \tan^{-1} g_0/R_0 \leq \pi/2, \qquad -\pi/2 \leq \tan^{-1} g_1/R_1 \leq \pi/2, \tag{15}$$

and where

$$\begin{aligned} g_0 &= 2\sqrt{\rho\rho_0}\cos \tfrac{1}{2}(\phi - \phi_0), \\ g_1 &= 2\sqrt{\rho\rho_0}\cos \tfrac{1}{2}(\phi + \phi_0 - 3\pi), \\ R_0^2 &= \rho^2 + \rho_0^2 - 2\rho\rho_0 \cos(\phi - \phi_0) + (z - z_0)^2, \\ R_1^2 &= \rho^2 + \rho_0^2 - 2\rho\rho_0 \cos(\phi + \phi_0 - 3\pi) + (z - z_0)^2. \end{aligned} \tag{16}$$

This new and particularly simple result, equations (13) through (16), may be derived by an involved direct analysis; it is better, however, to prove merely that this is the desired result.[2]

It may be verified by direct substitution that G_0 and G_1 separately and therefore G satisfy Laplace's equation. The boundary conditions appearing in equations (7) may be seen to be satisfied by noting that

$$\begin{aligned} G_0 &= G_0(\cos \tfrac{1}{2}(\phi + \phi_0)), \\ G_1 &= G_0(\cos \tfrac{1}{2}(\phi + \phi_0 - 3\pi)); \end{aligned} \tag{17}$$

and

$$\pm\, \partial G/\partial n = \partial G/\partial\phi = -\tfrac{1}{2}[\sin \tfrac{1}{2}(\phi - \phi_0) + \sin \tfrac{1}{2}(\phi + \phi_0 - 3\pi)]\, G_0' = 0 \quad \text{for } \phi = -\pi/2,\ 3\pi/2. \tag{18}$$

To prove that G satisfies the inhomogeneous part of the first of equations (7), we need only demonstrate that G varies as $1/R_0$ in the neighborhood of the source. Since $g_0 \sim 2\rho$ according to the first of equations (16) and $R_0 \sim 0$, we find from the first of equations (14) that $G_0 \sim 1/R_0$ as $R_0 \to 0$. And since R_1 remains finite, G does, in fact, vary as $1/R_0$ in the neighborhood of the source as it should. Finally, we note that the behavior at infinity is proper. As R_0 and therefore R_1 go to infinity we have $G_0 \sim 1/2R_0$ and $G_1 \sim 1/2R_1$ from equations (14). Since $R_1 \sim R_0$, we have $G \sim 1/2R_0 + 1/2R_1 \sim 1/R_0$, as it should.

It is of interest to note that the image function G_1, equation (14), remains finite even when the point of observation is coincident with the image point. This may be regarded as arising from the fact that the image is actually at the virtual point $\phi = 3\pi - \phi_0$ and is, therefore, not present in the real space where $-\pi/2 \leq \phi \leq 3\pi/2$.

[2] An interesting derivation of the present results has been obtained as a special case of the transient problem of a dipole established step-wise in time by J. R. Wait (1957) who had the present material by private communication.

MAGNETIC POTENTIAL

To compute the scalar magnetic potential we first write it as the sum of a source term and an image term as given by equations (11) and (13),

$$\psi = \psi_0 + \psi_1, \tag{19}$$

where

$$\psi_0 = \nabla^0 \cdot \boldsymbol{m} G_0/4\pi, \qquad \psi_1 = \nabla^0 \cdot \boldsymbol{m} G_1/4\pi. \tag{20}$$

Substituting the expressions for G_0 and G_1 as given by equation (14), (15), and (16) into equations (20), we obtain,

$$\begin{aligned} \psi_0 &= [\pi + 2\tan^{-1} g_0/R_0 + 2g_0R_0/X^2]\boldsymbol{m}\cdot\nabla^0(1/8\pi^2R_0) + (1/4\pi^2X^2)\boldsymbol{m}\cdot\nabla^0 g_0, \\ \psi_1 &= [\pi + 2\tan^{-1} g_1/R_1 + 2g_1R_1/X^2]\boldsymbol{m}\cdot\nabla^0(1/8\pi^2R_1) + (1/4\pi^2X^2)\boldsymbol{m}\cdot\nabla^0 g_1, \end{aligned} \tag{21}$$

where

$$X^2 = (\rho + \rho_0)^2 + (z - z_0)^2 = R_0^2 + g_0^2 = R_1^2 + g_1^2. \tag{22}$$

The derivatives appearing in equations (21) may be evaluated. In cartesian components we have

$$\begin{aligned} \nabla^0 g_0 &= (h_0\boldsymbol{e}_x - g_1\boldsymbol{e}_y)/2\rho_0, \\ \nabla^0 g_1 &= (h_1\boldsymbol{e}_x - g_0\boldsymbol{e}_y)/2\rho_0, \end{aligned} \tag{23}$$

where $\boldsymbol{e}_x$, $\boldsymbol{e}_y$ are unit vectors, $\boldsymbol{g}_0$ and $\boldsymbol{g}_1$ are given by the first two equations (16) and where

$$\begin{aligned} h_0 &= 2\sqrt{\rho\rho_0}\cos\tfrac{1}{2}(\phi + \phi_0), \\ h_1 &= 2\sqrt{\rho\rho_0}\cos\tfrac{1}{2}(\phi - \phi_0 - 3\pi); \end{aligned} \tag{24}$$

and

$$\begin{aligned} \nabla^0(1/R_0) &= \boldsymbol{R}_0/R_0^3, \\ \nabla^0(1/R_1) &= \boldsymbol{R}_1/R_1^3 - 2(x + x_0)\boldsymbol{e}_x/R_1^3, \end{aligned} \tag{25}$$

where the last two equations may be verified by noting that

$$\begin{aligned} R_0^2 &= (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2, \\ R_1^2 &= (x + x_0)^2 + (y - y_0)^2 + (z - z_0)^2. \end{aligned} \tag{26}$$

MAGNETIC FIELD

From equations (4) and (19), neglecting the case of coincident source and observer, we may write the magnetic field as the sum of a source term and an image term,

$$\boldsymbol{H} = \boldsymbol{H}_0 + \boldsymbol{H}_1 \tag{27}$$

where

$$\boldsymbol{H}_0 = -\nabla\psi_0, \qquad \boldsymbol{H}_1 = -\nabla\psi_1. \tag{28}$$

Substituting equations (21) through (25) into equations (28), we obtain

$$\begin{aligned} \boldsymbol{H}_0 = {} & [3\boldsymbol{m}\cdot\boldsymbol{R}_0\boldsymbol{R}_0 - \boldsymbol{m}R_0^2][\pi + 2\tan^{-1} g_0/R_0 + 2g_0R_0/X^2]/8\pi^2R_0^5 \\ & + \boldsymbol{R}_0\boldsymbol{m}\cdot[g_0\boldsymbol{R}_0 + R_0^2\nabla^0 g_0]/2\pi^2R_0^2X^4 \\ & - \boldsymbol{m}\cdot[\boldsymbol{R}_0 - g_0\nabla^0 g_0]\nabla g_0/2\pi^2X^4 - \nabla[\boldsymbol{m}\cdot\nabla^0 g_0]/4\pi^2X^2, \end{aligned} \tag{29}$$

$$\begin{aligned} \boldsymbol{H}_1 = {} & [3(\boldsymbol{m}\cdot\boldsymbol{R}_1 - 2(x + x_0)m_x)\boldsymbol{R}_1 - \boldsymbol{m}R_1^2 + 2m_xR_1^2\boldsymbol{e}_x] \\ & \times [\pi + 2\tan^{-1} g_1/R_1 + 2g_1R_1/X^2]/8\pi^2R_1^5 \\ & + \boldsymbol{R}_1\boldsymbol{m}\cdot[g_1(\boldsymbol{R}_1 - 2(x + x_0)\boldsymbol{e}_x) + R_1^2\nabla^0 g_1]/2\pi^2R_1^2X^4 \\ & - \boldsymbol{m}\cdot[\boldsymbol{R}_1 - 2(x + x_0)\boldsymbol{e}_x - g_1\nabla^0 g_1]\nabla g_1/2\pi^2X^4 \\ & - \nabla[\boldsymbol{m}\cdot\nabla^0 g_1]/4\pi^2X^2, \end{aligned} \tag{30}$$

where $\boldsymbol{R}_0$ and $\boldsymbol{R}_1$ are defined by equation (16) or (26) and are shown in Figure 1, g_0 and g_1 are defined by equations (16), $\nabla^0 g_0$ and $\nabla^0 g_1$ are given by equations (23) and (24), the arctangents are confined to the range from $-\pi/2$ to $+\pi/2$, X^2 is given by equation (22),

$$\begin{aligned} \nabla g_0 &= (h_0\boldsymbol{e}_x - g_1\boldsymbol{e}_y)/2\rho, \\ \nabla g_1 &= -(h_1\boldsymbol{e}_x + g_0\boldsymbol{e}_y)/2\rho, \end{aligned} \tag{31}$$

where h_0 and h_1 are given by equations (24), and where

$$\begin{aligned} \nabla[\boldsymbol{m}\cdot\nabla^0 g_0] &= [-h_1\boldsymbol{e}_z \times \boldsymbol{m} + g_0(m_x\boldsymbol{e}_x + m_y\boldsymbol{e}_y)]/4\rho\rho_0, \\ \nabla[\boldsymbol{m}\cdot\nabla^0 g_1] &= [h_0\boldsymbol{e}_z \times (\boldsymbol{m} - 2\boldsymbol{m}_x\boldsymbol{e}_x) + g_1(-m_x\boldsymbol{e}_x + m_y\boldsymbol{e}_y)]/4\rho\rho_0. \end{aligned} \tag{32}$$

CONCLUSIONS

The idealized problem of the electromagnetic response of a dyke of infinite conductivity and vanishing thickness to a slowly oscillating magnetic dipole can, surprisingly, be solved exactly in a simple closed form, equations (29) through (32). This result represents quite adequately the response of a dyke of large conductivity and small geometrical width. If the actual conductivity and width need to be known for purposes of identification of the ore and to estimate the size of the deposit, then it is necessary to refine the solution by approximate methods to be presented in a subsequent paper.

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RESPONSE OF THIN DYKE TO OSCILLATING DIPOLE*†

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ABSTRACT

A dyke of sulfide ore may be geophysically prospected by observing its response to a slowly oscillating magnetic dipole source. To a first approximation the field produced by a thin dyke is given by a dyke of infinite conductivity and vanishing thickness in a vacuum (Wesley, 1958, GEOPHYSICS, v. 23, p. 128). In order to identify the ore and to estimate the size of the deposit, it is necessary to consider further approximations involving the conductivity and thickness of the dyke. By a type of analytical continuation an approximation is found which agrees both with the exact solution for a dyke of infinite conductivity and vanishing thickness and with the exact solution (approximated only for $\omega\sigma$ large and also for $\omega\sigma$ small) for an infinite slab of finite conductivity and nonvanishing thickness, the dyke appearing as an infinite slab when both source and observer are near the dyke but far removed from the edge. The solution is very good provided the dyke is geometrically thin.

INTRODUCTION

This paper is a continuation of the article by Wesley (1958) to include the case of the response of a dyke of finite conductivity and nonvanishing thickness to a slowly oscillating magnetic dipole source. Coordinates and symbols used here are identical to those used in that article and need no further clarification here.

The approximate solution obtained is a type of analytical continuation from two exact solutions. In particular, the solution is in the form of a Green's function which reduces to the exact solution for a dyke of infinite conductivity and vanishing thickness when the conductivity is allowed to be infinite and the thickness zero (such that $\sigma t^2 \to \infty$, where t is the thickness and σ the conductivity of the dyke) and which reduces to the exact solution for the case of an infinite slab of finite conductivity and nonvanishing thickness (approximated only for $\omega\sigma$ large and for $\omega\sigma$ small) when both source and observer are near the dyke but far removed from the edge.

The solution of the problem of the response of an infinite slab to a slowly oscillating magnetic dipole source is presented here with only a very brief explanation, since the problem has been solved elsewhere and the techniques are well known, even if they are involved (Wait, 1951).

The approximate magnetic field components in a form useful for computation are not presented because of their length and the fact that they may be obtained by simple differentiations of the Green's functions, F_0/R_0 and F_1/R_1 as defined by equations (22) of this article.

RESPONSE OF SLAB TO OSCILLATING DIPOLE

Since this problem of the response of an infinite slab of finite conductivity

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and nonvanishing thickness to an oscillating magnetic dipole source may be solved exactly in integral form by standard techniques first used by Sommerfeld (1909), only the briefest outline is given here.

Introduction

Coordinates compatible with the dyke problem are obtained by choosing the x-axis perpendicular to the slab, the $Y(=y-y_0)$ axis vertical and in the plane of the slab, and the $Z(=z-z_0)$ axis horizontal and in the plane of the slab. The slab of finite conductivity, σ, and of nonvanishing thickness, t, is then defined by the infinite plane faces $x=-t/2$ and $x=+t/2$. The source dipole is taken on the x-axis at $x=x_0$ where $x_0 \geq t/2$. In addition to cartesian coordinates, we define cylindrical coordinates, r, θ, x, such that

$$r = \sqrt{Y^2+Z^2}, \qquad \theta = \tan^{-1}(Z/Y). \tag{1}$$

Using a magnetic Hertz vector, $\mathbf{\Pi}$, Maxwell's equations (Stratton, 1941, p. 29) yield

$$\begin{aligned} \nabla\nabla\cdot\mathbf{\Pi} - \nabla\times\nabla\times\mathbf{\Pi} + k^2\mathbf{\Pi} &= -\boldsymbol{m}\delta(\boldsymbol{R}_0), \\ \boldsymbol{H} &= k^2\mathbf{\Pi} + \nabla\nabla\cdot\mathbf{\Pi} \\ \boldsymbol{E} &= i\omega\mu\nabla\times\mathbf{\Pi}, \end{aligned} \tag{2}$$

where the propagation constant k is given by

$$k^2 = \omega^2\mu\epsilon + i\omega\mu\sigma. \tag{3}$$

The three regions under consideration are indicated by the subscript 1 for the slab $(-t/2 \leq x \leq t/2)$, the subscript 2 for the region containing the source $(x \geq t/2)$, and the subscript 3 for the region on the other side of the slab $(x \leq -t/2)$. Neglecting terms of order ω^2, in region 1, the slab, we choose $k_1=k$, $\sigma_1=\sigma$, $\mu_1=\mu_0$, and $\epsilon_1=\epsilon_0$. And in regions 2 and 3, the vacuum, we have k_2, $k_3=0$; σ_2, $\sigma_3=0$; μ_2, $\mu_3=\mu_0$; and ϵ_2, $\epsilon_3=\epsilon_0$. The propagation constant of interest for the slab is then

$$k^2 = i\omega\mu_0\sigma. \tag{4}$$

By virtue of the cylindrical symmetry about the x-axis, only the case of a magnetic dipole in the x direction and the case of a magnetic dipole in the y direction need be treated, the general solution being the appropriate linear combination of these two cases.

Integral Solution with x Dipole

From equations (2), the appropriate boundary conditions (Stratton, 1941, p. 37) and the standard techniques first used by Sommerfeld (1909), we obtain

the desired exact solution in integral form,

$$\Pi_{1xx} = 2\frac{m_x}{4\pi}\int_0^\infty d\lambda\lambda J_0(\lambda r)e^{-\lambda(x_0-t/2)}\{\lambda\sinh\gamma(x+t/2)+\gamma\cosh\gamma(x+t/2)\}/K,$$

$$\Pi_{2xx} = \frac{m_x}{4\pi}\int_0^\infty d\lambda J_0(\lambda r)\{e^{-|x-x_0|}+k^2\sinh\gamma t\, e^{-\lambda(x+x_0-t)}/K\}, \tag{5}$$

$$\Pi_{3xx} = 2\frac{m_x}{4\pi}\int_0^\infty d\lambda\lambda\gamma J_0(\lambda r)e^{\lambda(x-x_0+t)}/K,$$

where

$$K = (2\lambda^2 - k^2)\sinh\gamma t + 2\lambda\gamma\cosh\gamma t, \tag{6}$$

and

$$\gamma = \sqrt{\lambda^2 - k^2}, \tag{7}$$

the phase being chosen as zero for $\lambda\to\infty$ and arg $\{-ik\}$ for $\lambda=0$. The first letter subscript on the Π's in equations (5) refers to the direction of the source dipole; the second subscript refers to the particular component of the Hertz Π vector, only the x component being necessary to satisfy the boundary conditions in the present case.

Integral Solution with y Dipole

Since symmetry about the x-axis does not exist for the present case both an x and y component of the Hertz vector are required. Following the standard techniques as in the last section we obtain,

$$\Pi_{1yz} = 2\frac{m_y}{4\pi}\cos\theta\frac{\partial}{\partial r}\int_0^\infty d\lambda J_0(\lambda r)e^{-\lambda(x_0-t/2)}\{\gamma\cosh\gamma(x+t/2) + \lambda\sinh\gamma(x+t/2)\}/K,$$

$$\Pi_{2yz} = 2\frac{m_y}{4\pi}\cos\theta\frac{\partial}{\partial r}\int_0^\infty d\lambda J_0(\lambda r)e^{-\lambda(x+x_0-t/2)}\{\gamma\cosh\gamma t + \lambda\sinh\gamma t\}/K, \tag{8}$$

$$\Pi_{3yz} = 2\frac{m_y}{4\pi}\cos\theta\frac{\partial}{\partial r}\int_0^\infty d\lambda\gamma J_0(\lambda r)e^{\lambda(x-x_0+t)}/K,$$

$$\Pi_{2yy} = \frac{m_y}{4\pi}\left(\frac{1}{R_0}+\frac{1}{R'}\right),$$

all other components vanishing, where as before R_0 is the distance from source to observer and R' is the distance from the image (as mirrored in the front surface of the slab, $x=t/2$) to the observer,

$$R'^2 = (x + x_0 - t)^2 + Y^2 + Z^2. \tag{9}$$

Green's Function for Slab

In order to generate the approximate solution for the thin dyke problem it is necessary to express the solution in the vacuum on either side of the slab (but not, of course, inside the slab) in terms of a Green's function. In particular, from equations (2) setting $k=0$, since k_2, $k_3=0$, G_s is defined by

$$\boldsymbol{H} = \nabla\nabla\cdot\boldsymbol{\Pi} = -\nabla\nabla^0\cdot\boldsymbol{m}G_s/4\pi. \tag{10}$$

Thus, the appropriate solution of Laplace's equation which is symmetrical in source and observer coordinates is

$$G_s = 1/R_0 - u(x-x_0)I_0 + u(x+x_0)I_1, \tag{11}$$

where

$$\begin{aligned} I_0 &= \int_0^\infty d\lambda J_0(\lambda r)\, A_0(\lambda) e^{-\lambda|x-x_0|}, \\ I_1 &= \int_0^\infty d\lambda J_0(\lambda r)\, A_1(\lambda) e^{-\lambda|x+x_0|}, \end{aligned} \tag{12}$$

where

$$\begin{aligned} A_0 &= 1 - 2\lambda\gamma e^{\lambda t}/K, \\ A_1 &= -k^2 \sinh \gamma t\, e^{\lambda t}/K, \end{aligned} \tag{13}$$

where K is defined by equation (6). The function $u(x-x_0)$ is unity for source and observer on opposite sides of the slab but zero if they are on the same side; and, conversely, $u(x+x_0)$ is unity for source and observer on the same side of the slab but zero if they are on opposite sides. If we let $t\to 0$, we may write,

$$\begin{aligned} u(x-x_0) &\equiv \frac{1}{2}\left|\frac{x}{|x|} - \frac{x_0}{|x_0|}\right|, \\ u(x+x_0) &\equiv \frac{1}{2}\left|\frac{x}{|x|} + \frac{x_0}{|x_0|}\right|. \end{aligned} \tag{14}$$

It should be noted that the solution as given by equation (11) has been extended to include the case of the source on the negative x-axis, $x_0 \leq -t/2$, as well as on the positive x-axis, $x_0 \geq t/2$.

This result, equations (11) through (13), may be checked by noting that for $\sigma\to 0$, $k\to 0$, $K\to 2\lambda^2 \exp(\lambda t)$, and (Watson, 1948, p. 384)

$$\int_0^\infty d\lambda J_0(\lambda r) e^{-\lambda|x-x_0|} = 1/R_0, \tag{15}$$

we obtain the free space Green's function, $G_s = 1/R_0$, as we should. Also for

$\sigma \to \infty$ we obtain the correct solution

$$G_s = 1/R_0 + u(x + x_0)/R', \tag{16}$$

where R' is the distance from the image (as mirrored in the slab face nearest the source) to the observer, e.g., equation (9).

Approximate Evaluation of the Integrals

We have obtained an exact solution for the magnetic field in the vacuum on either side of the slab in terms of a single scalar Green's function, equation (11). But this simple exact solution cannot, unfortunately, be regarded as the final solution, since the very difficult task of evaluating the integrals has yet to be done. Here we are content to consider two simple cases, k large and k small, i.e., $\omega\sigma$ large and $\omega\sigma$ small, in order to generate two approximate evaluations of the integrals I_0 and I_1, equations (12).

Approximation of Integrals for Large k.—For large k most of the contribution to the integrals occurs in the region for which $\lambda < |k|$; and so, we expand A_0 and A_1 in power series in λ, substitute these series into I_0 and I_1, and integrate term by term to obtain a series approximation of the integrals. Expanding A_0 and A_1, equations (13), (6) and (7), in a power series in λ taking due care of the phase of γ, we have, to three terms,

$$\begin{aligned} A_0 &\approx 1 + 2(\lambda/k)\csc kt + 2(\lambda/k)^2 \csc kt[2\cot kt + kt], \\ A_1 &\approx 1 + (\lambda/k)[2\cot kt + kt] + (\lambda/k)^2[4\cot^2 kt + 2kt\cot kt + 2 + (kt)^2/2]. \end{aligned} \tag{17}$$

Substituting equations (17) into equations (12) and integrating according to equation (15), we obtain the desired series approximations of the integrals to three terms,

$$\begin{aligned} I_0 &\approx \frac{1}{R_0} - \frac{2\csc kt}{k}\,\frac{\partial}{\partial|x - x_0|}\,\frac{1}{R_0} + \frac{2\csc kt}{k^2}[2\cot kt + kt]\,\frac{\partial^2}{\partial|x - x_0|^2}\,\frac{1}{R_0}, \\ I_1 &\approx \frac{1}{R_1} - \frac{2\cot kt + kt}{k}\,\frac{\partial}{\partial|x + x_0|}\,\frac{1}{R_1} \\ &\quad + \frac{1}{2k^2}[4 + 8\cot^2 kt + 4kt\cot kt + (kt)^2]\,\frac{\partial^2}{\partial|x + x_0|^2}\,\frac{1}{R_1}, \end{aligned} \tag{18}$$

where R_0 and R_1 are the object and image distances, respectively, as defined in the paper by Wesley (1958).

Approximation of Integrals for Small k.—For small k most of the contribution comes from the saddle point $\gamma = 0$ (which may be examined in greater detail in the complex u plane defined by $\lambda = k \sin u$). Thus, we expand A_0 and A_1 in power series in γ, substitute in the integrals, and integrate term by term to obtain a series approximation of the integrals for k small. Expanding A_0 and A_1, equa-

tions (13), (6), and (7) in power series in γ we have to two terms

$$A_0 \approx \left[1 - \frac{2e^{kt}}{2 + kt}\right] + \frac{\gamma^2 kte^{kt}}{k^2(2 + kt)^2}\left[1 + kt + (kt)^2/3\right],$$
$$A_1 \approx -\frac{kte^{kt}}{2 + kt} + \frac{\gamma^2 kte^{kt}}{k^2(2 + kt)^2}\left[1 + kt + 5(kt)^2/6 + (kt)^3/3\right], \tag{19}$$

where the series continue in powers of γ^2 and not γ. Substituting equation (19) into equations (12) and integrating according to equation (15), we obtain the desired series approximation of the integrals to two terms

$$I_0 \approx \left[1 - \frac{2e^{kt}}{2 + kt}\right]\frac{1}{R_0} + \frac{kte^{kt}}{(2 + kt)^2}\left[1 + kt + (kt)^2/3\right]\left[\frac{\partial^2}{k^2\partial\,|\,x - x_0\,|^2} - 1\right]\frac{1}{R_0},$$
$$I_1 \approx -\frac{kte^{kt}}{2 + kt}\,\frac{1}{R_1} + \frac{kte^{kt}}{(2 + kt)^2}\left[1 + kt + 5(kt)^2/6 + (kt)^3/3\right]\left[\frac{\partial^2}{k^2\partial\,|\,x + x_0\,|^2} - 1\right]\frac{1}{R_1}. \tag{20}$$

REQUIREMENTS FOR SOLUTION OF THIN DYKE PROBLEM

An excellent approximation of the response of a dyke of finite conductivity and nonvanishing thickness to a slowly oscillating magnetic dipole source may be obtained by satisfying the following requirements:

1. The solution should be in the form of a Green's function, according to equation (10); that is, it must be a solution of Laplace's equation, symmetrical in source and observer coordinates, and with the proper behavior when the observer is near the source.

2. When the conductivity is allowed to become infinite, the thickness going to zero such that $t\sqrt{\omega\mu_0\sigma/2} \to \infty$, the solution should reduce to the exact Green's function obtained for the case of a dyke of infinite conductivity and vanishing thickness as given by Wesley, (1958).

3. When the source and observer are both near the dyke but far removed from the edge, the solution should be given by the approximate Green's function for the slab problem, equations (11) and (18) or by equations (11) and (20), whichever is appropriate.

4. When the conductivity is taken as finite and the thickness allowed to vanish, the solution should reduce to the free-space Green's function.

5. When the thickness is kept nonvanishing and the conductivity is allowed to go to zero, the solution should reduce to the free-space Green's function.

COMPARISON OF SLAB AND DYKE PROBLEMS

When the exact Green's function (Wesley, 1958) solution for the response of a dyke of infinite conductivity and vanishing thickness to a slowly oscillating magnetic dipole, G_d, is written,

$$G_d = 1/R_0 - F_0/R_0 + F_1/R_1, \tag{21}$$

where

$$\begin{aligned} 2\pi F_0 &= \pi - 2\tan^{-1}(g_0/R_0), \\ 2\pi F_1 &= \pi + 2\tan^{-1}(g_1/R_1), \end{aligned} \tag{22}$$

where as before

$$\begin{aligned} g_0 &= 2\sqrt{\rho\rho_0}\cos\tfrac{1}{2}(\phi - \phi_0), \\ g_1 &= 2\sqrt{\rho\rho_0}\cos\tfrac{1}{2}(\phi + \phi_0 - 3\pi), \end{aligned} \tag{23}$$

it is found that for both source and observer near the dyke but far removed from the edge that

$$\begin{aligned} F_0 &= u(x - x_0) \quad \text{for } t = 0, \\ F_1 &= u(x + x_0) \quad \text{for } t = 0, \end{aligned} \tag{24}$$

where $u(x-x_0)$ and $u(x+x_0)$ are defined by equations (14) and the preceding discussion. Substituting equations (24) into (21) and comparing with the slab problem equations (11) and (18) for the case $\sigma \to \infty$, we not only find agreement but are, in addition, led to attempt an approximation for the thin dyke by making the replacements

$$\begin{aligned} u(x - x_0)/R_0 \quad &\text{by} \quad F_0/R_0, \\ u(x + x_0)/R_1 \quad &\text{by} \quad F_1/R_1, \end{aligned} \tag{25}$$

in the approximate expressions (11) and (18) or (20) for the slab problem.

It is immediately seen, however, that the derivatives with respect to $|x-x_0|$ and $|x+x_0|$ that occur in equations (18) and (20) would no longer be possible since F_0/R_0 and F_1/R_1 are not functions of $|x-x_0|$ and $|x+x_0|$ but are, instead, functions of x and x_0 separately. We are led to the satisfactory replacement of these derivatives by requiring symmetry between source and observer coordinates as is required of any Green's function. Thus, the nth derivative is replaced as follows,

$$\begin{aligned} u(x - x_0)\frac{\partial^n}{\partial|x - x_0|^n}\frac{1}{R_0} \quad &\text{by} \quad \frac{1}{2^n}\left\{\frac{x - x_0}{|x - x_0|}\right\}^n\left(\frac{\partial}{\partial x} - \frac{\partial}{\partial x_0}\right)^n\frac{F_0}{R_0}, \\ u(x + x_0)\frac{\partial^n}{\partial|x + x_0|^n}\frac{1}{R_1} \quad &\text{by} \quad \frac{1}{2^n}\left\{\frac{x + x_0}{|x + x_0|}\right\}^n\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)^n\frac{F_1}{R_1}, \end{aligned} \tag{26}$$

where the operators on the right are identical to those on the left when the replacements (25) are made.

SOLUTION OF THIN DYKE PROBLEM

The approximate solution for the response of a dyke of finite conductivity an nonvanishing thickness to a slowly oscillating magnetic dipole is now obtained by making the replacements (26) in equations (11) and (18) or (20), to yield the Green's function,

$$G_{td} = 1/R_0 - Q_0 + Q_1, \tag{27}$$

where for large k to three terms

$$\begin{aligned} Q_0 \approx & \left\{1 - \frac{\csc kt}{k} \frac{x - x_0}{|x - x_0|}\left(\frac{\partial}{\partial x} - \frac{\partial}{\partial x_0}\right)\right. \\ & \left. + \frac{\csc kt}{2k^2}[2\cot kt + kt]\left(\frac{\partial}{\partial x} - \frac{\partial}{\partial x_0}\right)^2\right\}\frac{F_0}{R_0}, \\ Q_1 \approx & \left\{1 - \frac{2\cot kt + kt}{2k} \frac{x + x_0}{|x + x_0|}\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)\right. \\ & \left. + \frac{1}{8k^2}[4 + 8\cot^2 kt + 4kt\cot kt + (kt)^2]\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)^2\right\}\frac{F_1}{R_1}; \end{aligned} \tag{28}$$

or for small k to two terms

$$\begin{aligned} Q_0 \approx & \left\{1 - \frac{2e^{kt}}{2 + kt} - \frac{kte^{kt}}{(2 + kt)^2}[1 + kt + (kt)^2/3]\right. \\ & \left. \times\left[1 - \frac{1}{4k^2}\left(\frac{\partial}{\partial x} - \frac{\partial}{\partial x_0}\right)^2\right]\right\}\frac{F_0}{R_0}, \\ Q_1 \approx & -\frac{kte^{kt}}{2 + kt}\left\{1 + \frac{1 + kt + 5(kt)^2/6 + (kt)^3/3}{2 + kt}\right. \\ & \left. \times\left[1 - \frac{1}{4k^2}\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)^2\right]\right\}\frac{F_1}{R_1}, \end{aligned} \tag{29}$$

where F_0 and F_1 are defined by equations (22) and k the propagation constant is given by equation (4). The magnetic field may be obtained by substituting G_{td}, equation (27), for G_s in equation (10).

Since k is complex and instrumentally it is easy to distinguish an "in-phase" component of the magnetic field, Re $\{H\}$, from an "out-of-phase" component of the magnetic field, Im $\{H\}$, it is useful to distinguish an "in-phase" Green's function, Re $\{G\}$, from an "out-of-phase" Green's function, Im $\{G\}$.

Defining an electrical thickness,

$$\xi = t/\delta = t\sqrt{\omega\mu_0\sigma/2}, \tag{30}$$

where δ is the skin depth, we have

$$kt = (1 + i)\xi. \tag{31}$$

We now consider two cases, one for ξ very large and one for ξ very small.

In-Phase Green's Function for ξ Very Large

Substituting equation (31) into equations (27) and (28), letting ξ become very large, and taking the real part of the resulting Green's function, we have,

$$\begin{aligned} \mathrm{Re}\{G_{tb}\} \approx\ & 1/R_0 - F_0/R_0 + F_1/R_1 \\ & - \frac{1}{2}t(1 - 1/\xi)\frac{x + x_0}{|x + x_0|}\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)\frac{F_1}{R_1} \\ & + \frac{1}{8}t^2(1 - 2/\xi)\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)^2 \frac{F_1}{R_1}. \end{aligned} \tag{32}$$

Out-of-Phase Green's Function for ξ Very Large

Taking the imaginary part of the equation which led to equation (32) we have

$$\mathrm{Im}\{G_{td}\} \approx \frac{t}{2\xi}\left\{\frac{x + x_0}{|x + x_0|} - \frac{1}{2}t(1 - 1/\xi)\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x}\right)\right\}\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial x_0}\right)\frac{F_1}{R_1}. \tag{33}$$

In-Phase Green's Function for ξ Very Small

Substituting equation (31) into equations (27) and (29), expanding the coefficients in powers of ξ, and taking the real part of the resulting Green's function, we have to the third power in ξ,

$$\mathrm{Re}\{G_{td}\} \approx 1/R_0 + \tfrac{1}{2}\xi(1 - \xi^2/6)F_0/R_0 - \tfrac{1}{2}\xi(1 - \xi^2/2)F_1/R_1. \tag{34}$$

where only the first term has been preserved. The series obtained, equations (29), is actually asymptotic; and, thus, for $\xi \to 0$ the second and subsequent terms must be dropped because they become infinite.

Out-of-Phase Green's Function for ξ Very Small

Taking the imaginary part of the equation which led to equation (34) we have

$$\mathrm{Im}\{G_{td}\} \approx \tfrac{1}{2}\xi(1 + \xi + \tfrac{1}{2}\xi^2)F_0/R_0 - \tfrac{1}{2}\xi(1 + \xi + \tfrac{1}{2}\xi^2)F_1/R_1. \tag{35}$$

CONCLUSION

We may readily verify that our solution as given by equations (27) and (28) or (29) (or as further approximated by equations (32), (33), (34), and (35)) does yield the desirable characteristics as listed under the section "Requirements for Solution of Thin Dyke Problem" when the appropriate expressions are used. It may be noted, when the conductivity becomes infinite, the electrical thickness ξ becoming infinite, that equation (32) which still involves t reduces to the slab problem, equation (16) with R' expanded in a power series in t, for source and observer near the dyke but far removed from the edge. Because of the large conductivity of sulfide ore, equations (32) and (33) probably represent the most practical results.

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GEOPHYSICS, VOL. XXIII, No. 1 (JANUARY, 1958), PP. 144–153 1 FIG.

DISCUSSIONS ON "A THEORETICAL STUDY OF INDUCED ELECTRICAL POLARIZATION"*

EDITOR'S NOTE: The series of discussions on the subject paper (Frische and von Buttlar, 1957) reaches agreement that a contribution has been made by Dr. Wait's suggested experimental method for measuring the induced polarization ratio $\Delta\phi/V$ of a two-layer flat earth containing an aquifer. There is disagreement on the value of the "dielectric constant" of the aquifer as to whether its magnitude is of the order of unity or of 10^6. Experimental evidence is cited in support of each position.

It is hoped that these discussions may serve to stimulate additional experimental investigations.

FIRST DISCUSSION†

JAMES R. WAIT‡

The analysis in the quoted paper is an attempt to calculate the induced polarization response of a two-layer flat earth. The upper layer is a homogeneous overburden of thickness h with a resistivity ρ_1 and a dielectric constant of ϵ_1. The lower (semi-infinite) medium which is the "aquifer" has a resistivity ρ_2 and dielectric constant ϵ_2. The value of the relaxation voltage as seen at the potential electrodes "immediately after" the current is shut off is designated $\Delta\phi$. The A's[1] of the above paper present a method for calculating the ratio $\Delta\phi/V$ where V is the steady voltage across the potential electrodes during the time of current flow.

Specific comments concerning the paper are as follows:

(1) p. 690. The potential $d\phi$ due to the polarization of the elementary volume $d\tau$, at distance r, is given by the A's as

$$d\phi = \frac{|\vec{P}| \cos\theta}{4\pi\epsilon r^2} d\tau$$

where $\vec{P}$ is the polarization vector, θ is the angle between the direction of the dipole moment vector and the position vector $\vec{r}$. Such an equation is only valid in a homogeneous lossless medium of dielectric constant ϵ for nonvarying fields. Neither of these conditions is satisfied in the A's application of this equation.

The A's then claim that $\Delta\phi$ is simply obtained by integrating $d\phi$ over the volume of the aquifer. Such an assumption is obviously not valid since the volume elements are not independent of one another.

(2) p. 691. The proof given by the A's that the current distribution in the aquifer is independent of polarization is misleading. The equation for the normal current density should be, actually,

$$J_z = -\left(\sigma + \epsilon\frac{\partial}{\partial t}\right)\frac{\partial\psi}{\partial z}. \qquad (1)$$

After the current has been flowing for a sufficiently long time (>60 secs. say),

* Frische and von Buttlar, 1957.

† Manuscript received by the Editor, August 15, 1957.

‡ 350 30th Street, Boulder, Colorado.

[1] A's will be used as an abbreviation for the authors, namely, Mr. Frische and Dr. von Buttlar.

the term containing $\partial/\partial t$ can be dropped, and, of course, we then have the usual condition for direct current in a two-layer ground, and the standard methods are applicable. To say that the current is independent of polarization, however, is not correct since the effective conductivity is a function of the polarization properties of the aquifer.

(3) p. 693. The image sources introduced by the authors will only satisfy the boundary conditions during the time of steady current (static regime). At the moment the current is interrupted, the polarization field as calculated by the authors does not satisfy the appropriate conditions at the interfaces between the media.

In view of the above remarks, the validity of the A's analysis might be questioned. The following alternative approach is presented which has a logical physical basis. Furthermore, the necessity for any complicated volume integrations are circumvented by making use of existing and rigorous formulas borrowed from resistivity analysis.

The starting point is to take the Laplace Transform of equation (1) above, to give[2]

$$J_z(s) = -(\sigma + s\epsilon)\frac{\partial \psi(s)}{\partial z} \tag{2}$$

where

$$J_z(s) = \int_0^\infty J_z(t)e^{-st}dt \tag{3}$$

it being assumed that $J_z(t) = 0$ for $t < 0$. Similarly

$$\psi(s) = \int_0^\infty \psi(t)e^{-st}dt. \tag{4}$$

The inversion of the preceding equation is

$$\psi(t) = \frac{1}{2\pi i}\int_{-i\infty}^{i\infty} \psi(s)e^{st}ds \tag{5}$$

and therefore

$$J_z(t) = -\frac{1}{2\pi i}\int_{-i\infty}^{i\infty} (\sigma + s\epsilon)\frac{\partial \psi(s)}{dz}e^{st}ds. \tag{6}$$

It is thus clear that the transient problem is most easily solved by transforming it to the complex frequency regime. The boundary value problem of the two-layer earth is now readily solved since layer (1) and layer (2) are simply specified

[2] σ and ϵ are functions of s since they are not constants in the time domain.

to have complex resistivities $\rho_1(s)$ and $\rho_2(s)$, respectively, whence

$$\rho_1(s) = \frac{1}{\sigma_1 + s\epsilon_1} \quad \text{and} \quad \rho_2(s) = \frac{1}{\sigma_2 + s\epsilon_2}.$$

A step-function current pulse $I(t)$ is now applied to the first current electrode (S_0 in the A's Fig. 1), that is

$$I(t) = I_0 u(t)$$

where

$$u(x) = 1 \text{ for } x > 0$$
$$= 0 \text{ for } x < 0$$

and consequently

$$I(s) = I_0/s.$$

The transform of the potential, $\psi(s)$, at some point a distance a from S_0 on the surface of the two layer ground is thus given by

$$\psi(s) = \frac{I_0 G(a, s)}{2\pi s}$$

$$G(a, s) = \rho_1(s)\left\{a^{-1} + 2\sum_{n=1}^{\infty}\left[\frac{\rho_2(s) - \rho_1(s)}{\rho_2(s) + \rho_2(s)}\right]^n [a^2 + (2nh)^2]^{-1/2}\right\}. \tag{7}$$

The transform of the voltage between the two potential electrodes of a Wenner array of spacing a resulting from the current $I(t)$ in the current electrodes, is obtained by a simple superposition of the function $\psi(s)$ to give

$$V(s) = \frac{I_0 W(s)}{2\pi s}$$

where

$$W(s) = 2G(a, s) - 2G(2a, s).$$

The voltage $v(t)$ is now obtained from the inversion

$$v(t) = \frac{1}{2\pi i}\int_{-i\infty}^{+i\infty} V(s)e^{st}ds. \tag{9}$$

The initial value theorem for Laplace Transforms leads to

$$v(0) = \lim_{s\to\infty} sV(s) = \frac{I_0 W(\infty)}{2\pi}$$

and the corresponding final value theorem leads to

$$v(\infty) = \operatorname*{Lim}_{s \to 0} sV(s) = \frac{I_0 W(0)}{2\pi}.$$

In other words, the initial and final values of the step-function response are related to the infinite and zero frequency responses respectively.

In the case of an interrupted steady current I, the initial value which is designated $\Delta\phi$ by the A's is $v(\infty) - v(0)$ and the A's voltage V is simply $v(\infty)$. Therefore

$$\frac{\Delta\phi}{V} = \frac{v(\infty) - v(0)}{v(\infty)} = \frac{W(0) - W(\infty)}{W(0)}.$$

It is permissible to write

$$W(s) = \frac{\rho_a(s)}{a}$$

where $\rho_a(s)$ is defined as a complex apparent resistivity, therefore

$$\frac{\Delta\phi}{V} \cong \frac{\rho_a(0) - \rho_a(\infty)}{\rho_a(0)}.$$

The induced-polarized response is thus defined in terms of the limiting low frequency value $\rho_a(0)$ of the apparent resistivity and the limiting high frequency value $\rho_a(\infty)$. $\rho_a(0)$ and $\rho_a(\infty)$ can be computed directly from the usual two-layer resistivity charts from the specified limiting values of $\rho_1(0)$ and $\rho_1(\infty)$ for the upper layer and $\rho_2(0)$ and $\rho_2(\infty)$ for the lower layer. These pairs of values are related to the induced polarization responses of the material in layer (1) and layer (2). That is

$$\left.\frac{\Delta\phi}{V}\right]_1 = \frac{\rho_1(0) - \rho_1(\infty)}{\rho_1(0)}$$

and

$$\left.\frac{\Delta(\phi)}{V}\right]_2 = \frac{\rho_2(0) - \rho_2(\infty)}{\rho_2(0)}.$$

The foregoing analysis tacitly neglects all electromagnetic propagation effects. For example at the instant the current is interrupted, the fields are not solutions of Laplace's equation. Actually $\Delta\phi/V$ is unity at $t=0$ since the field takes a finite time to decay from V to $\Delta\phi$. However, if by $t=0$ we mean some small time where propagation effects have vanished, then $\Delta\phi$ is physically significant. Correspondingly, $\rho_a(\infty)$ is taken to be the resistivity at some high but finite frequency where it tends to approach a substantially constant value.

The foregoing brief discussion is not claimed to be comprehensive. The phenomena of induced polarization is very complicated as pointed out by the A's. Starting from the fact that the complex resistivity is a function of frequency, however, deductions concerning the transient responses can be computed for a variety of situations.

AUTHORS' FIRST REPLY§

RICHARD H. FRISCHE‖ AND HARO VON BUTTLAR‖

Dr. James R. Wait[3] invited us to comment on his discussion of our paper in the July, 1957, issue of GEOPHYSICS. We are grateful for this opportunity, since a clarification of some basic concepts appears necessary.

The first part of W.'s discussion is based on the assumption that the "dielectric constant" of an aquifer is of the order of 10^6, as suggested by the work of Evjen (1948) and Keller and Licastro (1955), so that the quantity $\epsilon\omega/\sigma$ becomes of the order of a few percent. As pointed out, however, in our article (Frische and von Buttlar, 1957, p. 705–706), this value is obtained from an interpretation of data pertaining to the relaxation of the charge in the ground and does not hold for the charging-up process. In the latter, dielectric-constant values close to unity have to be used (p. 705). Values of 10^6 for the dielectric constant lead to induced-polarization responses completely incompatible with the experimental data.

If current is supplied by exciting the ground with a step-function potential, the current reaches its equilibrium value within a few milliseconds and not after about 60 secs., as used by W. to demonstrate a large value of ϵ. When the current is turned off, the elementary dipoles in the aquifer will remain in position and only slowly decay to zero, owing to ionic diffusion on and between the clay particles. The relaxation mechanism is not understood completely as yet. Certainly, however, an exponential law involving σ and ϵ does not hold; the relaxation proceeds more in a hyperbolic fashion, as expected for diffusion (Vacquier et al., 1957).

The elementary dipoles created in the aquifer can be represented only approximately, of course, by a volume polarization, since the sand and clay particles have macroscopic size. In view, however, of the length of the distances a and r, the use of the equation

$$d\phi = \frac{|\vec{P}| \cos\theta}{4\pi\epsilon r^2} d\tau$$

and of an integration procedure based on the law of superposition of potentials

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[3] "W." will be used as an abbreviation for Dr. Wait.

appears justified. Any interaction between the dipoles in the aquifer must be small and would not alter our equation (18) (p. 695).

Since our experimental value for the "dielectric constant" of the aquifer is not very different from unity, we have neglected this difference in using our equation (24) (p. 696), thus treating the aquifer and overburden system, after the polarization has been created, as a homogeneous medium having a permittivity close to ϵ_0.

In view of these considerations, the objections raised by W. concerning our article do not seem very serious. His calculation of the relation between the induced-polarization effect and the resistivity responses at different frequencies, on the other hand, deserves attention. He suggests an extension of the calculation, yielding a different experimental method for measuring the induced polarization ratio $\Delta\phi/V$, even though it does not become clear from his paper what value should be employed for the "dielectric constant." Also, W.'s study does not supply new information as to the polarization mechanism. It will be interesting to see whether his determinations of this ratio compare with the experimental data as well as ours.

SECOND DISCUSSION*

JAMES R. WAIT†

It appears that the A's do not agree with my comments. It might help to clarify my position if a more specific example is considered.

Contrary to the A's assertion, the charging up and the relaxation processes are identical for a linear medium. By a linear medium we mean one in which the induced polarization is essentially independent of voltage gradient. Such is the case as indicated in Figure 3 in the paper by Vacquier et al. (1957). As a consequence of this, the induced polarization decay curves after the interruption of a long current pulse (i.e., 120 secs.), have the same functional form as the build up of the voltage at the potential electrodes on the application of the current. The verification of this hypothesis is obtained by noting that the three of the decay curves in the paper by Vacquier et al. (p. 664, Fig. 2), can be deduced from the fourth. The decay curve $v(t)$ for the 120-second excitation time can be assumed to be nearly representative of the step-function response of the medium. The corresponding decay curve for an excitation time of t_1 secs. is then given simply by

$$v(t) - v(t + t_1) \text{ for } t > 0.$$

The first term is the response due to a negative step-function current at $t=0$,

* Manuscript received by the Editor September 23, 1957.

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and the second term is the response due to the positive step at $t = -t_1$. The curves by Vacquier et al. are replotted in Figure 1 along with the three derived curves. The agreement is good. The small discrepancies can probably be attributed to either experimental error or the fact that an excitation time of 120 secs. is not long enough to regard it as infinite. In any case, it is clear that the response of a finite current pulse is simply the superposition of the build-up response from the leading edge and decay due to the trailing edge of the pulse.

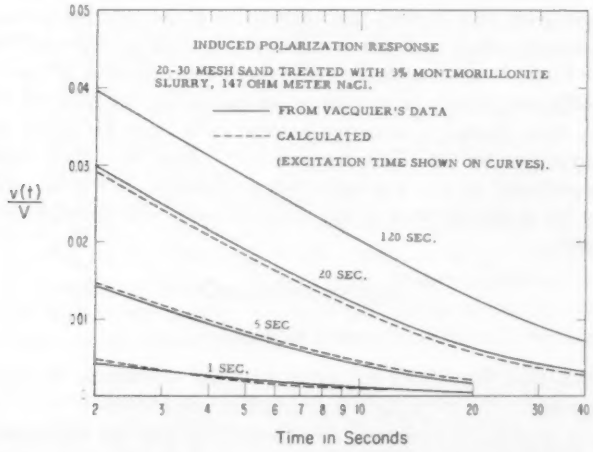

FIG. 1. Calculation of Vacquier's curves on the assumption that the decay curve for the 120 second excitation time is nearly representative of the step-function response of the medium.

It will now be shown that the decay curves of Vacquier et al., do indeed imply that the relative dielectric constants are very large and not essentially unity as contended by the A's. The analysis given in my earlier discussion did not specify any functional form for the variation of σ and ϵ with frequency. The A's objected that my results were only valid for constant values of σ and ϵ. This is not so. However, for the sake of convenience in what follows the induced-polarization decay curve after the interruption of a long current pulse (i.e. > 60 secs.), can be written

$$\frac{v(t)}{V} = 1 - a - B \log t$$

for a wide range of times t. This is indicated in Figure 1 where the abscissa is proportional to the logarithm of time and the ordinate is linear. This is a good approximation for the behavior of the decay curves at times from a few milliseconds to not greater than about 30 secs. The build up $A(t)$ of the pulse then has the

form

$$\frac{A(t)}{V} = a + B \log t$$

noting that $A(t) = V - v(t)$.

Now it is well known that transient response $A(t)$ of a linear system specifies the frequency characteristics. In the present case, the transfer impedance $Z(\omega)$ between the voltage and current electrodes is related to $A(t)$ by

$$I(\omega) \frac{Z(\omega)}{i\omega} = \left[\int_0^\infty A(t) e^{-st} dt \right]_{s=i\omega}$$

where $I(\omega)$ is the steady state current at an angular frequency ω. This leads to

$$\frac{Z(\omega)}{R} = a - 0.577\, B - B \log \omega - i \frac{\pi}{2} B$$

where R is the transfer resistance (i.e., $R = Z(0)$) and is a real quantity.

This result is most interesting because it indicates that for a near-linear dependence of $A(t)$ [or $v(t)$] with $\log t$, the phase angle of the impedance is essentially a constant. For a homogeneous sample,

$$Z(\omega) \text{ varies as } \frac{1}{\sigma + i\omega\epsilon}$$

and since $|Z(\omega)| \cong R$ it follows that to a first order

$$\frac{\pi}{2} B \cong \left(\frac{\epsilon\omega}{\sigma} \right).$$

Over the frequency range of interest (0.1 c/s to 1,000 c/s), this implies that the dielectric constant ϵ varies as the reciprocal of the frequency.

To calculate $(\epsilon\omega/\sigma)$ from the experimental data Figure 1, we use the equation

$$\frac{\epsilon\omega}{\sigma} = \frac{\pi}{2V} \frac{v(t_1) - v(t_2)}{\log (t_2/t_1)}$$

or if for convenience

$$t_1 = 2 \text{ secs.}$$

$$t_2 = 20 \text{ secs.}$$

we have

$$\frac{\epsilon\omega}{\sigma} \cong 0.682 \left[\frac{v(2)}{V} - \frac{v(20)}{V} \right].$$

Using the data for the 120 secs. excitation we find

$$\frac{\epsilon\omega}{\sigma} \cong 0.0184.$$

For a frequency of 10 c/s and a conductivity of 10^{-3} mhos/meter this yields

$$\epsilon/\epsilon_0 = 3.3 \times 10^5$$

for the dielectric constant relative to free space. Values of this order have been measured by Dr. George Keller of the Geological Survey and were quoted by the A's.

The A's have not answered my main objection to their method of calculating $\Delta\phi$ which simply superimposes potentials of adjacent volume elements.[4] Furthermore their basic potential equation is only valid in a dielectric medium where the conduction currents are negligible. Actually the denominator is more like $4\pi\sigma r^2$ rather than $4\pi\epsilon r^2$ and $|\overrightarrow{P}|$ should be the current-moment of the equivalent dipole.

The A's agreement between theory and experiment is more apparent than real since "the scale of the ordinates of the experimental curves was adjusted to fit the theoretical curves." Furthermore, the A's do not explain any of the temporal behavior of the decay curves. The fact that the A's compute a value of the relative dielectric constant near unity is a further indication that their initial hypothesis and formulation is questionable.

It is admitted that the physical nature of induced polarization is only partially understood. Nevertheless, since the phenomenon is linear, then, in a macroscopic sense, the medium can be described electrically in terms of a frequency dependent dielectric constant and conductivity. Or more conveniently, it may be desirable to lump these together into a complex resistivity given by

$$\rho(s) = \frac{1}{\sigma + s\epsilon}$$

in the Laplace-Transform notation. In most cases s can be replaced by $i\omega$. The formulas of resistivity analysis then can be generalized to alternating current by simply admitting the appropriate complex values of the various resistivity factors involved. Using this approach the complicated volume integrations used by the A's are avoided and no assumption need be made about the non-interaction of volume elements in the polarizable layers.

I should like to take this opportunity to thank my colleagues A. A. Brant, H. O. Siegel, and L. S. Collett for many stimulating discussions on this subject.

[4] $\Delta\phi$ is equivalent to $v(t)$ as $t \to 0$.

AUTHORS' SECOND REPLY*

RICHARD H. FRISCHE† AND HARO VON BUTTLAR†

We have received a copy of W.'s second discussion on the induced polarization problem. After reading it thoroughly, our position is unchanged. The aquifer is not a "linear medium" because the motions of the ions are essentially different with and without electric field. Therefore, values for the dielectric constant calculated on the decay part of the curves do not have to agree with the ones calculated from the magnitude of the induced polarization signal. A ratio ϵ/ϵ_0 of 10^5 would yield a maximum induced polarization signal of about $\Delta\phi/V=0.5$, which has never been observed.

We think that W. is carrying the model of a leaky dielectric too far; it just will not describe all the properties of an aquifer.

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GEOPHYSICS, VOL. XXIII, NO. 1 (JANUARY, 1958), PP. 154–163 5 FIGS.

A SLIDE RULE FOR NEAR-SURFACE REFRACTION PROBLEMS*

W. A. KNOX†

ABSTRACT

The paper describes a slide-rule useful for determining reflection time corrections for multilayer weathering problems. It is also useful to the seismic reviewer in computing a correction factor for data which have been reduced by overly-simplified corrections.

INTRODUCTION

While multiple layer weathering problems occur from time to time almost everywhere, there are some areas in which a multilayer correction problem is the rule. Western Canada is an example where several layers of low and intermediate velocity, unconformably overlie the older section having a relatively constant velocity. Thralls and Mossman (1952) encountered a similar problem in parts of Central United States. Corrections to reflection times are required to remove the effects of the various near-surface layers. The necessary corrections are usually determined from refraction data. To solve the equations arising from the problem and its consequences, a simple slide rule has been designed. It is illustrated in Figure 1.

APPLICATION OF THE SLIDE RULE

The primary application of the refraction slide rule is to solve for the thickness of, and vertical time through, one or more refractors. The quantities needed for the solution are the velocities and corresponding intercept times from properly processed refraction graphs.

Its secondary purpose is the calculation of the vertical delay time due to each refractor, with respect to some constant velocity originally used to correct the seismic record to the datum or reference plane. That is, let the record be corrected from the base of shot (or from the base of weathering, or, for that matter, even from the surface) to the datum, using a constant datum velocity, without regard for possible intermediate velocity layers sandwiched between the base of the weathering and the datum. The slide rule provides a ready answer to the question: What is the additional time required to correct for the delay due to the introduction of one or more low and intermediate velocity layers that were previously ignored? This problem occurs quite frequently in the review and recomputation of old seismic work.

ASSUMPTIONS

In the practical application of the slide rule solution to near-surface problems,

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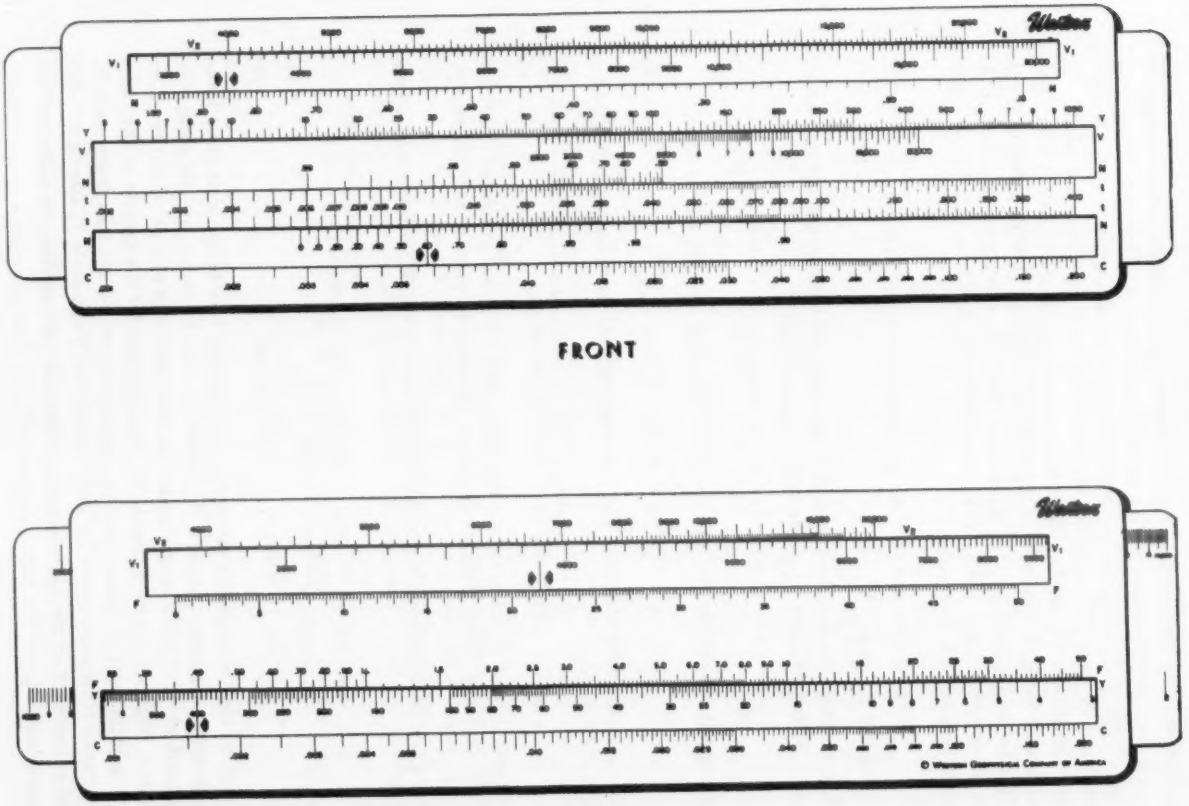

FIG. 1. Refraction slide rule.

it is assumed that the velocity remains constant with depth for each layer and that the well-known straight-path refraction formula applies (Nettleton, 1940). Although the slide rule was designed primarily for near-surface work, it can be applied to any refraction problem for which the basic equations are valid.

In the field the dip of the refractor is not ordinarily computed. A depth point is calculated for each profile. The dip is proportional to the difference in depths.

It will be assumed in this discussion, that the refraction information has been processed in such a way that the depth points, times, or additives apply directly beneath the shot point.

SOLUTION OF REFRACTION PROBLEMS WITH THE SLIDE RULE

Two-Velocity Problem

The solution for the thickness of a layer Z_0, from intercept times t_0 and t_1, due to velocities V_0 and V_1 is the well-known relation

$$Z_0 = (t_1 - t_0)V_0/2 \cos \alpha_{01} \tag{1}$$

assuming the shot originated at the upper boundary of layer Z_0. As usual,

$$V_0/V_1 = \sin \alpha_{01} = N_{01}, \tag{2}$$

where α_{01} is the critical angle. The one-way vertical time through the layer of thickness Z_0 is

$$T_0 = Z_0/V_0 = (t_1 - t_0)/2 \cos \alpha_{01}. \tag{3}$$

Figures 2a and 2b illustrate the ray paths and refraction graph for the simple two-velocity case. From Figure 2b, since t_0 is equal to zero, it drops out of (1) and (3).

For a slide rule solution, equations (1), (2), and (3) must be put in logarithmic form:

$$\log Z_0 = \log t_1 + \log V_0 - \log (2 \cos \alpha_{01}), \tag{1a}$$

$$\log N_{01} = \log V_0 - \log V_1, \tag{2a}$$

$$\log T_0 = \log t_1 - \log (2 \cos \alpha_{01}) \tag{3a}$$

To solve the two-velocity problem, use the front face of the slide rule. From the top suite of scales, compute N_{01} from V_0 and V_1 (note: on the slide rule, scales marked "V_1" will always be used for the lesser of a pair of velocities under discussion, while the scales marked "V_2" will be used for the greater of the two). On the middle bank of scales, set N_{01} over t_1; above V_0, read Z_0 from scale Y. Above 10,000 (this is the index for the V scale) read T_0 on scale Y, after a suitable mental adjustment of the decimal point. The slide rule settings are illustrated in Figures 2c and 2d.

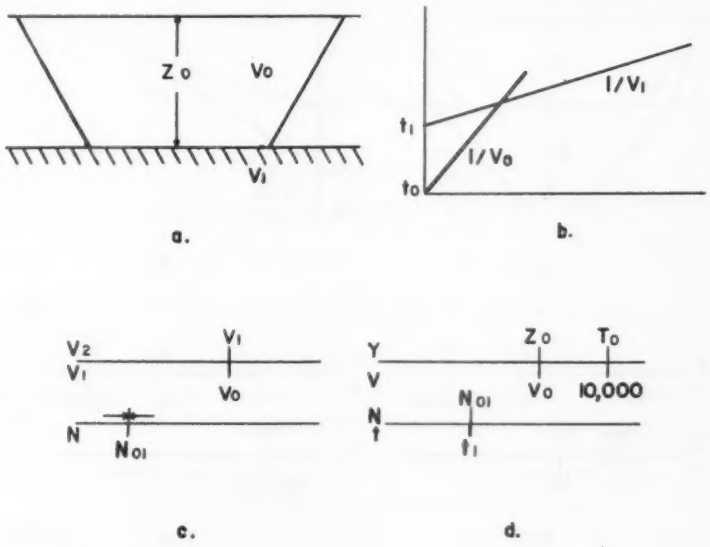

FIG. 2. a. Ray paths for two velocity case.
b. Refraction graph.
c. and d. Slide rule settings for the two-velocity case.

Multi-Velocity System

The ray paths and refraction graph for a three-velocity case are shown in Figures 3a and 3b. The solutions for Z_0 and T_0 are computed as for the two-velocity case, assuming the shot originated at the upper boundary of Z_0.

We can compute the thickness of the second layer Z_1, and the vertical time T_1, from the equations

$$Z_1 = (t_2 - t_{02})V_1/2 \cos \alpha_{12}, \tag{4}$$

$$T_1 = Z_1/V_1, \tag{5}$$

where

$$t_{02} = 2Z_0 \cos \alpha_{02}/V_0, \tag{6}$$

and

$$\sin \alpha_{02} = V_0/V_2 = N_{02},$$

$$\sin \alpha_{12} = V_1/V_2 = N_{12}.$$

The slide rule solution is performed in three steps the last two of which are illustrated in Figures 3c and 3d. First evaluate the N's using the top suite of

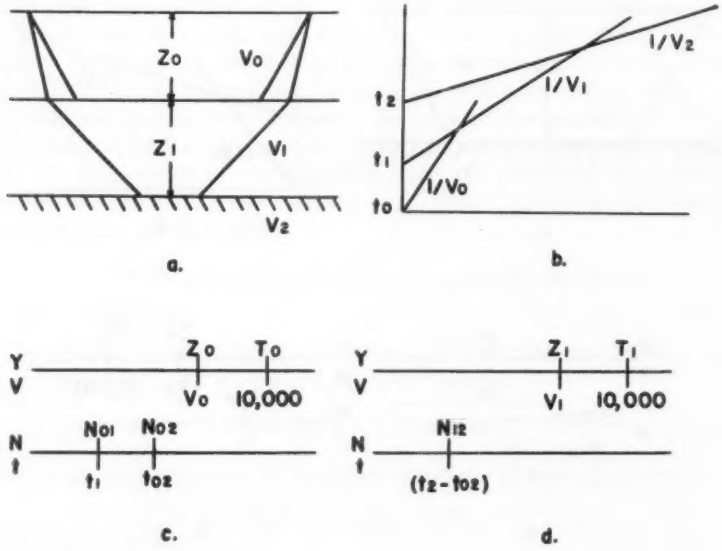

FIG. 3. a. Ray paths for the three-velocity case.
b. Refraction graph.
c. Slide rule settings, first layer.
d. Slide rule settings, second layer.

scales. Next, compute Z_0 and T_0 as before, but without moving the slide setting, read t_{02} from the t scale beneath N_{02}. Finally, using V_1, (t_2-t_{02}), and N_{12} as entries, solve for Z_1 and T_1. The total time through the two near-surface layers is T_0+T_1.

When the shot is d feet within the layer Z_0, equations (1) and (3) are modified to

$$Z_0 = d/2 + t_1V_0/(2 \cos \alpha_{01}) \tag{1b}$$

$$T_0 = d/2V_0 + t_1/(2 \cos \alpha_{01}) \tag{3b}$$

When the shot hole penetrates Z_1 the correct value of Z_0 will be twice the value of equation (1) and

$$Z_1 = (d - Z_0)/2 + (t_2 - t_{02})V_1/2 \cos \alpha_{12} \tag{4a}$$

where t_{02} must be determined from the up-hole time.

A four velocity problem can be solved similarly, with the aid of the additional equations

$$Z_2 = (t_3 - t_{03} - t_{13})V_2/2 \cos \alpha_{23}, \tag{7}$$

$$T_2 = Z_2/V_2 \tag{8}$$

where

$$t_{03} = 2Z_0 \cos \alpha_{03}/V_0, \tag{9}$$

$$t_{13} = 2Z_1 \cos \alpha_{13}/V_1, \tag{10}$$

and

$$\sin \alpha_{03} = V_0/V_3 = N_{03},$$

$$\sin \alpha_{13} = V_1/V_3 = N_{13},$$

$$\sin \alpha_{23} = V_2/V_3 = N_{23}.$$

The quantities t_{03} and t_{13} are obtained from the slide rule as was t_{02} in the three-velocity solution.

It is seldom necessary to peel off more than one or two velocity layers below Z_0 before penetrating to the constant velocity formation. It is doubtful that a five-velocity solution would be required for near-surface correction problems.

CORRECTION ADDITIVES DUE TO THE INTRODUCTION OF ONE OR MORE REFRACTORS

Introduction

In the review of old seismic work, it is frequently found that one or more variable velocity refractors went unrecognized, and the records were reduced to the reference plane with little regard for anything other than layer Z_0. Sometimes, even in current work, the field office routine makes it desirable to ignore temporarily the effect of possible intermediate velocity layers. It becomes necessary therefore to compute a correction additive. This additive must correct for the time delay due to the introduction of one or more relatively low velocity refractors, without making a detailed recomputation of the seismic record. Such correction additives can be computed rapidly and easily with the slide rule.

Correction Additive, General Case

Refer to Figure 4a. Let the original seismic record reduction to the datum or reference plane be computed as

$$2AB/V_d,$$

where the datum velocity $V_d = V_3$, and where V_3 is assumed to be the constant formation velocity. From a study of the refraction data it is later found necessary to introduce three layers: Z_0, Z_1, and Z_2, between the surface and the datum. The corresponding velocities are

$$V_0 < V_1 < V_2 < V_3 = V_d.$$

The additives C_i, required to correct for the additional delay time due to the

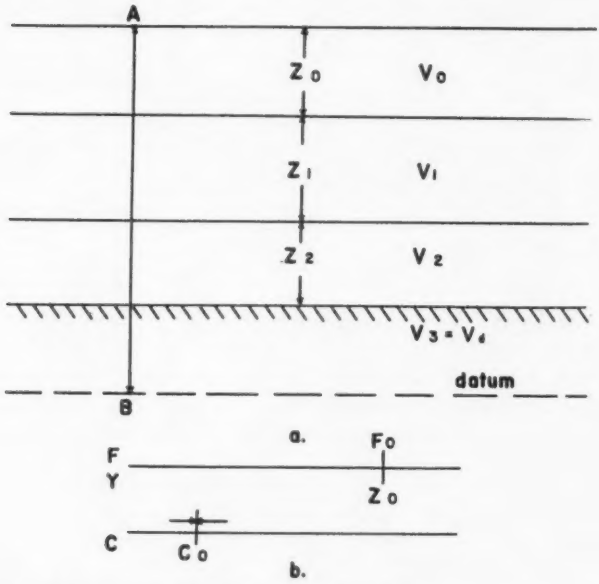

FIG. 4. a. Correction additive, three layers, four velocities.
b. Slide rule settings for the correction additive, first layer.

three layers are

$$\begin{aligned} C_0 &= 2Z_0(1/V_0 - 1/V_d), \\ C_1 &= 2Z_1(1/V_1 - 1/V_d), \\ C_2 &= 2Z_2(1/V_2 - 1/V_d), \end{aligned} \tag{11}$$

and the total correction is ΣC_i.

For layer Z_0, let

$$F_0 = 2(1/V_0 - 1/V_d) \times 10^5, \tag{11a}$$

then

$$C_0 = Z_0 \times F_0 \times 10^{-5}. \tag{11b}$$

In logarithmic form (12b) is

$$\log C_0 = \log Z_0 + \log F_0 - 5. \tag{11c}$$

Multiplication and subsequent division by 10^5 is required to keep the units on the F scale of the slide rule within manageable limits.

Equation (11a) is solved on the back of the slide rule using the upper tier

of scales (use scale V_2 for V_d). The solution for (11b) is performed on the bottom scale suite, entering Z_0 on scale V. Corrections for the remaining layers Z_1 and Z_2 are computed similarly. The corrections for each layer are subtracted from the original record reduction to the datum for the velocity conditions specified in the first paragraph.

Apply a suitable shot depth correction for the layer containing the shot.

Special Solution for Two-Velocities Excluding V_0

Following the method of the previous section, it was necessary to compute the thickness of the various layers from the front of the slide rule, then to calculate the correction additives from the back of the rule. In the special case where but two velocities are involved exclusive of V_0, where $V_d = V_2$, where the time delay due to layer Z_0 was correctly removed in the initial record reduction to the datum, and finally, where the shot is in layer V_1, a greatly simplified solution is possible.

Refer to Figure 5a. Consider V_2 to be the formation velocity in this case. The original record reduction to the datum in terms of time was

$$Z_0/V_0 + AB/V_d + A'B'/V_d = Z_0/V_0 + 2AB/V_d.$$

With the introduction of layer Z_1, the original record time reduction is in error

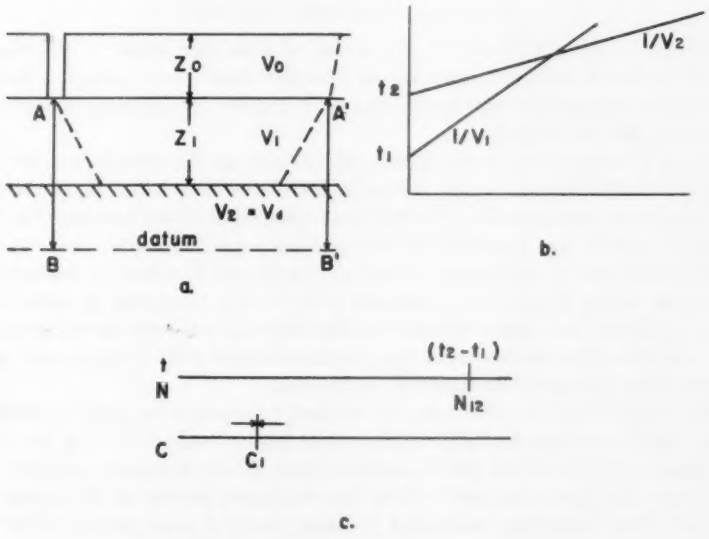

FIG. 5. a. Correction additive, two velocities excluding V_0.
b. Refraction graph.
c. Slide rule solution.

and the correction C_1, for the additional delay time through Z_1 is

$$C_1 = 2Z_1/V_1 - 2Z_1/V_d = 2Z_1(1/V_1 - 1/V_d).$$

Let us substitute the right hand member of (4) for Z_1, which we can do since $V_d = V_2$. Then

$$C_1 = [(t_2 - t_{02})V_1/\cos a_{12}](1/V_1 - 1/V_2).$$

Upon simplifying,

$$C_1 = (t_2 - t_{02})(\sec a_{12} - \tan a_{12}). \tag{12}$$

In logarithmic form for adaptation to slide rule solution, (12) becomes

$$\log C_1 = \log (t_2 - t_{02}) + \log (\sec a_{12} - \tan a_{12}). \tag{12a}$$

If the difference between the observed intercept t_1, and the computed quantity t_{02}, is small, we can insert $(t_2 - t_1)$ in (12), which is simply the difference in intercept times as observed on the refraction graph.

C_1 is computed on the slide rule using the lower suite of scales, front face. The settings are shown in Figure 5b. The correction additive C_1, is thus computed in a single step, using the observed intercept time difference, without the need for determining the actual thickness of layer Z_1.

CONSTRUCTION OF THE SLIDE RULE

While the general theory of the layout of slide rule scales is described in readily available texts and need not be discussed here (Davis, 1943), a description of the arrangement and numbering of the scales, as used on this particular slide rule, may be helpful.

All of the scales except the upper suite of three on the reverse face, are ordinary C and D slide rule scales, although some have been folded or inverted for convenience in manipulation. The middle N scale on the front face is divided into units of $1/\cos \alpha$, but numbered in terms of $\sin \alpha = N$. Similarly, the bottom N scale is measured in units of $\sec \alpha - \tan \alpha$. The V_1 and V_2 scales on the back face are linear scales divided into intervals of $1/V$, but numbered in terms of V. The top F scale is a linear measure of the difference between the reciprocals of the velocities. The various scales have been numbered to fit the units and ranges of quantities ordinarily encountered in the field.

In constructing the slide rule, the original drawings were photographed and later printed on dimensionally stable, white paper, using black ink for direct-reading scales and red ink for the inverted ones. Where necessary, windows were die-cut in the sheets destined to form the stationary portion of the device. The printed sheets were then laminated between sheets of clear plastic. After trimming, the two outer faces, separated by thin spacers, were cemented together at the top and bottom edges. Insertion of the slide completed the assembly. The

instrument is rugged and attractive. It can be manufactured as described in quantities up to 100, at considerably less expense than would be possible using the ordinary commercial processes.

ACKNOWLEDGEMENT

I should like to thank Mr. E. Won for his criticism of the manuscript, Miss D. Stark for preparing certain drawings, and the Western Geophysical Company for permission to publish this paper. Mr. Carl Savit is due credit for advice in details of design and construction of the slide rule.

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Jakosky, J. J., 1950, Exploration geophysics: Los Angeles, Trija Publishing Co.

Nettleton, L. L., 1940, Geophysical prospecting for oil: New-York, McGraw-Hill Book Company, Inc.

Thralls, H. M., and Mossman, R. W., 1952, Relation of seismic correlations to surface geology: Geophysics, v. 17, p. 218–228.

DEPARTMENTS

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,794,949. E. H. L. Hedstrom and R. V. Tegholm. Iss. 6/4/57. App. 2/3/55 and 5/10/55.

Electromagnetic Induction Method and Apparatus for Prospecting. An airborne electromagnetic prospecting system in which exciting coils on the plane generate a circularly-polarized magnetic field and the space gradient of elliptical polarization produced by anomalies is detected by means of two birds towed at different distances behind the plane.

U. S. No. 2,796,235. M. D. Quigley. Iss. 6/18/57. App. 5/24/52. Assign. Sinclair Oil & Gas Co.

Process of Geophysical Prospecting. A method of electrical prospecting for oil in which the subsurface resistivity is measured along traverses to locate high-resistivity dikes.

U. S. No. 2,799,003. T. J. Nowak. Iss. 7/9/57. App. 2/16/53. Assign. Union Oil Co. of Calif.

Electric Logging Method and Apparatus. An electric logging or prospecting system using radioactive electrodes in order to reduce polarization effects at the ground contact.

U. S. No. 2,800,629. G. F. Tagg. Iss. 7/23/57. App. 2/16/55 and 2/13/56. Assign. Evershed & Vignoles Ltd.

Earth Resistance Measuring Equipment. A four-electrode resistivity meter in which the ratio of the ground current to the potentiometer current is indicated.

GRAVIMETRIC PROSPECTING

U. S. No. 2,801,794. W. W. Garvin and J. R. Leggett. Iss. 8/6/57. App. 3/1/51. Assign. California Research Corp.

Apparatus for Geophysical Prospecting. An analog computer for determining the vertical gravity of a distribution of mass in which the mass is divided into vertical prisms each of whose effect at a mapping point is determined by an a-c network in which resistance is analogous to horizontal distance and reactance is analogous to vertical distance and the currents from the respective prisms are added at the mapping point and indicated.

MAGNETIC PROSPECTING

U. S. No. 2,803,798. K. A. McLeod. Iss. 8/20/57. App. 3/20/45. Assign. U.S.A.

Portable Magnetometer. A magnetometer having a high-permeability magnetic antenna with a D'Arsonval meter movement between its pole pieces and with the coil deflection observed with constant current.

RADIOACTIVITY PROSPECTING

U. S. No. 2,795,703. I. B. Berlman and L. D. Marinelli. Iss. 6/11/57. App. 3/16/54. Assign. U.S.A.

Apparatus for Counting Fast Neutrons in the Presence of Gamma Rays. A device for measuring the density of fast neutrons in the presence of gamma rays by using two scintillation counters whose scintillation vessels have the same amount of electrons but one vessel contains a considerably greater amount of hydrogen atoms, the difference between their counts being a measure of the neutron density.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,795,704. H. Bryant, G. F. Erickson and S. G. Kaufmann. Iss. 6/11/57. App. 4/15/54. Assign. U.S.A.

Neutron Ion Chamber. A device for measuring neutron flux in the presence of other radiations having two juxtapositioned U-shaped electrodes with a grounded motor-driven disk rotated between them, both sides of one half of the disk being coated with B^{10} so as to be neutron responsive, and with each electrode connected to ground through a resistor and common battery and the difference in potential across the resistor indicated.

U. S. No. 2,796,411. R. E. Zirkle and H. J. Curtis. Iss. 6/18/57. App. 1/29/47. Assign. U.S.A.

Radiation Shield. A neutron shield made of polymerized acrylate plastic incorporating a boron compound so as to provide at least 0.1 gram of boron per sq. cm. of shield area.

U. S. No. 2,796,529. P. Morrison. Iss. 6/18/57. App. 8/23/48. Assign. U.S.A.

Radiation Shield. A device for absorbing fast neutrons escaping from a radioactive source having an inside layer of iron, then a layer of compressed wood fibers, and alternating layers of iron and cellulose acetate containing dispersed boron.

U. S. No. 2,799,780. I. W. Ruderman. Iss. 7/16/57. App. 9/3/53. Assign. Isomet Corp.

Neutron Scintillation Counter. A device for detecting neutrons in the presence of gamma rays having alternating layers of scintillator about 10 microns thick and boron glass about 100 microns thick which gives rise to alpha particles upon neutron capture.

SEISMIC PROSPECTING

U. S. No. 2,794,512. J. L. Martin. Iss. 6/4/57. App. 7/27/53. Assign. The Atlantic Refining Co.

Means for Determining Acoustical Velocity and Attenuation Characteristics of Subterranean Formations. An acoustic logging system using an acoustic source and two spaced piezoelectric receivers, one receiver near the source being arranged to pick up energy reflected from the formation wall and the other distant receiver used to pick up refraction energy travelling through the formation.

U. S. No. 2,794,965. W. J. Yost. Iss. 6/4/57. App. 5/25/53. Assign. Socony Mobil Oil Co., Inc.

Statistical Interpretation of Seismograms. A method of analyzing seismic reflection records in which a curve of variation of autocorrelation function with increasing time delay is first determined for a trace dominated by noise, and also for each reflection trace, and the first curve reproduced and passed through a circuit which nullifies it and the curves for the successive reflection traces then reproduced through the same channel to bring out the reflections.

U. S. No. 2,794, 966. M. D. McCarty. Iss. 6/4/57. App. 8/28/53. Assign. Socony Mobil Oil Co., Inc.

Selective Mixing of Seismic Signals. A method of seismic recording in which the channel signals are successively rapidly sampled and the rate of sampling filtered from the composite record, the sampling rate being varied during the course of the record.

U. S. No. 2,795,287. J. A. Sharpe. Iss. 6/11/57. App. 4/8/52. Assign. Seismograph Service Corp.

Apparatus for Seismic Reflection Mapping. Apparatus for compositing seismic traces recorded in reproducible form in which a number of traces are simultaneously scanned by play-back heads which are initially moved with respect to each other to compensate for fixed time variations of the separate traces, and which are moved during the play-back so as to compensate for differences in step-out due to different shot-detector distances for the various traces.

U. S. Re. 24,330 (Original No. 2,604,955). J. E. Hawkins. Iss. 6/18/57. App. 4/18/46, 7/29/52, and 7/13/54. Assign. Seismograph Service Corp.

System for Analysis of Seismographic Records. A system for analyzing seismograms in which the

traces are reproduced by a pair of spaced pick-ups and the signals from the first pick-up used to control the filtering or otherwise alter a characteristic of the signal from the second pick-up.

U. S. No. 2,796,756. W. A. Yates and M. Davidson. Iss. 6/25/57. App. 9/30/54. Assign. U.S.A.

Vibration Calibrator. A vibration measuring device in which the vibration moves a metallic member close to the coils of a mutual inductance, one coil being excited by a regulated high-frequency carrier and the change in carrier in the other coil amplified and measured with a peak voltmeter.

U. S. No. 2,796,863. W. von Wittern. Iss. 6/25/57. App. 12/18/52. Assign. U.S.A.

Pressure Responsive Pick-Up Measuring Device. A variable air-gap pressure transducer having a magnetic diaphragm near the poles of an a-c excited electromagnet and detecting reluctance changes by a secondary winding connected to a phase-sensitive rectifier.

U. S. No. 2,797,399. L. W. Camp and W. A. Daniel. Iss. 6/25/57. App. 3/8/55. Assign. Bendix Aviation Corp.

Underwater Transducer. A hydrophone having a rubber case with longitudinally-polarized cylinders of barium titanate mounted between a diaphragm exposed to the water and an insulating rear wall.

U. S. No. 2,797,911. J. L. Montgomery. Iss. 7/2/57. App. 10/17/51.

Accelerometer. An accelerometer in which a long period is attained without lengthening the deflection by connecting to the suspended seismic mass one or more rotatable inertia masses which are rotated by displacement of the seismic mass.

U. S. No. 2,797,912. R. M. Trostler. Iss. 7/2/57. App. 10/21/53. Assign. Sperry-Rand Corp.

Acceleration-Responsive Device. An accelerometer having a bar magnet mechanically suspended in a liquid and with electrodes connected in a bridge circuit contacting the liquid so that movement of the magnet unbalances the bridge, and also having feed-back coils near each end of the magnet connected in the circuit to oppose motion of the magnet.

U. S. No. 2,798,211. N. J. Smith. Iss. 7/2/57. App. 4/15/54. Assign. California Research Corp.

Seismic Prospecting Method and Apparatus. A marine seismic cable arrangement in which each group of pressure detectors is connected to the primary of its impedance-matching transformer in the cable, and the secondaries of two transformers are connected to a common cable lead so as to reduce the number of cable conductors required.

U. S. No. 2,798,972. G. B. Booth. Iss. 7/9/57. App. 2/16/56. Assign. Textron Inc.

Vibration Pickup. An electromagnetic vibrometer having a coil suspended on a pivoted cantilever arm, the coil surrounding an inner pole piece which receives flux from magnetic circuits both above and below the pole piece.

U. S. No. 2,799,015. N. W. Bell. Iss. 7/9/57. App. 12/27/54. Assign. Consolidated Electrodynamics Corp.

Vibration Indicator. A vibration alarm in which the signal from a self-generating pick-up is filtered and rectified and operates an indicator and alarm-circuit relay.

U. S. No. 2,800,583. I. H. Gerks. Iss. 7/23/57. App. 10/21/55. Assign. Collins Radio Co.

Means for Determining Cross-Correlation Coefficients, Such as Between Diversity Signals. An apparatus for determining the cross-correlation between two diversity signals in which each operates a pair of relays controlling the flow of current from positive and negative current sources to an integrating circuit whose total voltage is indicated.

U. S. No. 2,800,639. B. D. Lee. Iss. 7/23/57. App. 3/28/50 and 12/28/53. Assign. The Texas Co.

Method and Apparatus for Analysis of Seismographic Records. A system for normalizing a multichannel seismogram in which the step-out is computed vectorially by an a-c analog computer which automatically displaces the pickups the proper amount during a reproduction of the seismogram.

U. S. No. 2,803,001. E. M. McNatt. Iss. 8/13/57. App. 6/2/52. Assign. Esso Research and Engineering Co.

Wave Detection in Seismic Prospecting. A seismic prospecting system in which the earth waves are detected by means of a microphone suspended in the air above the detection point.

U. S. No. 2,803,515. S. J. Begun, E. R. Sarratt, J. F. Blaha, and D. R. Christian. Iss. 8/20/57. App. 1/5/54. Assign. Clevite Corp.

Recording Apparatus. A magnetic seismograph recorder in which a rotating drum carries a multichannel magnetic tape and also a visual recording tape, the seismic signals being recorded with magnetic heads and immediately after completion of the record it is played back and re-recorded in visual form by means of an oscillographic recording pen.

U. S. No. 2,803,801. R. D. Cunningham. Iss. 8/20/57. App. 4/10/46. Assign. U.S.A.

Wave Analyzing Apparatus. A speech analyzing apparatus in which the signal is filtered to suppress lower frequencies, rectified and used to overdrive an amplifier to obtain square waves which are differentiated, and negative peaks clipped, and the resulting signal averaged and indicated, the process being repeated in successive channels to indicate the presence of higher frequencies.

U. S. No. 2,803,809. A. E. Tilley. Iss. 8/20/57. App. 5/18/54. Assign. California Research Corp.

Method and Apparatus for Timing Seismic Recordings. A timing system for a seismogram analyzer having a recorder-reproducer and a permanent recorder and arranged so that the timing marks are put on the original recording so that subsequent seismic trace reproductions through filters may be made while reproducing the timing lines in their original form.

U. S. No. 2,804,509. W. F. Knauert and I. Michalko. Iss. 8/27/57. App. 7/17/52. Assign. Sonotone Corp.

Inertia Type Electromechanical Sound Transducing Device. A suspended-magnet variable air-gap reluctance-type sound transducer having the magnetic armature fastened to the case and having resilient arms which serve as stops to prevent excessive movement of the suspended system.

U. S. No. 2,804,603. W. T. Harris. Iss. 8/27/57. App. 7/24/51. Assign. The Harris Transducer Corp.

Sound Meter. A pressure geophone having two cylindrical magnetostriction or capacitor type pressure-sensitive transducers subjected to ambient pressure with one of them shielded against acoustic pressure.

WELL LOGGING

U. S. No. 2,794,260. J. C. Kinley. Iss. 6/4/57. App. 6/27/55.

Pipe Calipers. A wire line caliper device having a clock-released lock which releases the caliper arms at a preset time.

U. S. No. 2,794,951. R. A. Broding and W. B. Allen. Iss. 6/4/57. App. 8/27/53. Assign. Socony Mobil Oil Co., Inc.

Dynamic Cable Measuring System. A well-logging cable measuring device which magnetically marks the cable and counts lengths between the magnetic marking transducers, the distance between the transducers being varied slightly in response to a strain gauge which measures cable tension, so as to correct the measured length for changes in tension.

U. S. No. 2,795,856. C. E. Reesby and O. R. Smith. Iss. 6/18/57. App. 11/25/55. Assign. Halliburton Oil Well Cementing Co.

Control Mechanism for Elements in Well Tools. A device for controlling well tools and having a solenoid-actuated valve which allows hydraulic fluid under well pressure to flow through a hydraulic motor to a chamber at atmospheric pressure.

U. S. No. 2,797,976. R. Ring. Iss. 7/2/57. App. 12/3/53. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Instrument. A multi-shot photographically-recording well surveying apparatus that is run through the drill string and records inclination and compass reading.

U. S. No. 2,799,004. R. R. Thompson. Iss. 7/9/57. App. 4/13/53. Assign. Esso Research and Engineering Co.

Electrical Well Logging System. An electric logging system using a pair of horizontally-spaced current electrodes and a pair of horizontally-spaced potential electrodes in the same vertical plane as the current electrodes and vertically-spaced from them.

U. S. No. 2,799,946. F. M. Mayes. Iss. 7/23/57. App. 6/8/55. Assign. Sun Oil Co.

Tubing Caliper. A tubing caliper having light spring-actuated calipering arms which move the armature of a variable inductance to change the frequency of an oscillator, both the oscillator output and the output of a fixed frequency oscillator being recorded in the apparatus.

U. S. No. 2,802,951. D. O. Seevers. Iss. 8/13/57. App. 8/28/54. Assign. California Research Corp.

Frequency Transforming System for Well Bore Signaling. A system for using a standard electric-logging cable for radioactivity logging in which sharp pulses are rapidly recorded by a c-r beam on an electrostatic storage surface which is scanned to transmit the integrated pulses to the surface at a lower frequency.

U. S. No. 2,803,526. T. J. Nowak. Iss. 8/20/57. App. 12/3/54. Assign. Union Oil Co. of Calif.

Location of Water-Containing Strata in Well Bores. A method of locating water-injection strata by running a thermal log under normal operating conditions, then injecting a chemical such as finely-divided sodium in kerosene which has an exothermic reaction when mixed with water, and running a second thermal log.

U. S. No. 2,803,796. N. A. Schuster. Iss. 8/20/57. App. 5/21/53. Assign. Schlumberger Well Surveying Corp.

Electrical Apparatus for Well Logging. An electric logging system in which the current distribution near the electrode array is controlled by an auxiliary current from an amplifier whose gain is automatically adjusted in response to the potential difference between two pick-up electrodes.

See also Patents 2,799,003 listed under Electrical Prospecting and 2,794,512 listed under Seismic Prospecting.

MISCELLANEOUS

U. S. No. 2,794,338. J. Murphy, L. S. Gournay and M. O. Johnson. Iss. 6/4/57. App. 1/12/54. Assign. Socony Mobil Oil Co., Inc.

Determination of Pore Size Distribution in Large Core Samples. A pore-size distribution measuring apparatus having a cylinder into which a core may be placed and mercury forced into the core under pressure.

U. S. No. 2,795,377. R. J. Loofbourrow, R. B. Stelzer and C. B. Scotty. Iss. 6/11/57. App. 11/26/52. Assign. The Texas Co.

Electrical Analogues. A barrier for an electrolytic potentiometric model having electrically-

insulated lead contacts immersed in an electrolyte containing lead acetate, acetic acid and sodium nitrate so as to eliminate passivity at the barrier electrodes.

U. S. No. 2,795,952. D. M. Stewart. Iss. 6/18/57. App. 9/20/54. Assign. Esso Research and Engineering Co.

Retrievable Pressure Recording Bomb and Choke. A wire line pressure gauge and choke for use with a formation tester arranged so that the fluid passes the pressure gauge before going through the choke.

U. S. No. 2,798,116. J. H. Wiens. Iss. 7/2/57. App. 10/11/50. Assign. 30% to Reed C. Lawlor.

Aerial Survey System. An aerial mapping system employing television transmission from the survey plane to a base station and using in the plane linear scanning transverse to the plane's motion, the received image being reproduced transverse to motion of a film strip.

U. S. No. 2,798,666. W. F. Brown, Jr. Iss. 7/9/57. App. 12/8/53. Assign. Sun Oil Co.

Electrical Analogs. A field-exploring electrode system for a reservoir analyzer having at least three pairs of electrodes symmetrically arranged at diametrically-opposite points of a circle whose center is the observation point, and a computer which resolves the three potential differences into orthogonal components of the field gradient.

U. S. No. 2,799,561. R. W. Rochon. Iss. 7/16/57. App. 11/17/54. Assign. Monarch Logging Co., Inc.

Method and Apparatus for Determining Hydrocarbon Content of Solid Earth Formation Samples. A core-testing system in which the core is placed in a calibrated chamber and the pressure reduced in successive steps with the amount of volatile hydrocarbon extracted at each step determined by a hot-filament detector.

U. S. No. 2,800,972. E. W. Jacobson and B. M. Wedner. Iss. 7/30/57. App. 8/20/53. Assign. Gulf Research & Development Co.

Drive Chain Adjuster for Amphibious Vehicles. A drive-chain adjuster for a marsh buggy which permits the operator without dismounting to vary the wheel base by bodily moving the dead axle which carriers one set of driving wheels.

U. S. No. 2,801,410. Y. Ikeuchi and I. Ikeuchi. Iss. 7/30/57. App. 6/1/56.

Device for Locating Submerged Objects. A sonde with two electrodes having file-like teeth and which are connected to an indicator so that when the teeth contact a metallic object it completes the circuit.

U. S. No. 2,802,172. W. F. Mueller and C. F. Rust. Iss. 8/6/57. App. 7/16/53. Assign. Socony Mobil Oil Co., Inc.

Core Sample Resistivity Cell. A device for measuring the resistivity of a core sample having a box with electrode plates which are spring pressed against the core and two sets of circumferentially-spaced electrodes which contact the cylindrical surface of the core.

U. S. No. 2,802,173. R. G. Nisle. Iss. 8/6/57. App. 3/1/54. Assign. Phillips Petroleum Co.

Core Saturation Distribution Measurement and Apparatus Therefor. A system for measuring core saturation distribution along a core being flooded in a tightly-fitting electrically-insulating tube by passing an audio-frequency a-c longitudinally through the core and observing the potential distribution along the core by means of movable capacitative electrodes outside the insulating tube.

SELECTED LIST OF U. S. PATENTS ISSUED DURING JUNE, JULY, AND AUGUST OF 1957

Patent No.	*Subject**
2,794,260[a]	44
2,794,338[a]	88
2,794,345	16
2,794,396	136
2,794,512[a]	8
2,794,594	312, 68
2,794,605	224
2,794,862	484
2,794,924	168, 196
2,794,926	196
2,794,949[a]	132
2,794,951[a]	40
2,794,954	324
2,794,965[a]	360
2,794,966[a]	356
2,794,973	200
2,795,133	140
2,795,142	16
2,795,287[a]	360
2,795,376	68
2,795,377[a]	68
2,795,378	68
2,795,395	404
2,795,475	324
2,795,651	224
2,795,665	188
2,795,701	236
2,795,703[a]	308
2,795,704[a]	308
2,795,756	168
2,795,776	68
2,795,780	316
2,795,781	316
2,795,782	316
Re.24,330[a]	360
2,795,856[a]	44
2,795,952[a]	288
2,795,954	200
2,795,955	200
2,795,957	16, 68
2,795,991	168
2,796,022	48
2,796,023	48
2,796,218	68
2,796,235[a]	124
2,796,314	324
2,796,317	324
2,796,359	224
2,796,411[a]	308
2,796,467	484
2,796,496	484
2,796,503	428
2,796,529[a]	308
2,796,549	68
2,796,566	68
2,796,594	16
2,796,598	68
2,796,756[a]	380
2,796,758	496
2,796,765	288
2,796,833	48
2,796,834	136
2,796,863[a]	484
2,796,884	200
2,796,986	228
2,797,066	104
2,797,263	224
2,797,264	224
2,797,284	200
2,797,330	236
2,797,379	16
2,797,399[a]	484
2,797,403	324
2,797,410	316
2,797,411	316
2,797,412	316
2,797,580	16
2,797,581	16
2,797,609	196
2,797,702	200
2,797,862	68
2,797,864	68
2,797,865	68
2,797,866	68
2,797,911[a]	4
2,797,912[a]	4
2,797,976[a]	520
2,798,116[a]	444
2,798,162	236
2,798,164	308
2,798,191	288
2,798,211[a]	360
2,798,378	80, 332
2,798,666[a]	68
2,798,682	16
2,798,787	324
2,798,854	196
2,798,902	436
2,798,956	236
2,798,972[a]	492
2,799,003[a]	116, 124, 308
2,799,004[a]	116
2,799,015[a]	492
2,799,089	200
2,799,157	140
2,799,164	16
2,799,165	148
2,799,169	16
2,799,171	68
2,799,224	48
2,799,449	68
2,799,450	68
2,799,461	16
2,799,474	392
2,799,552	324
2,799,561[a]	88
2,799,609	224
2,799,732	224
2,799,758	460
2,799,780[a]	308
2,799,787	12
2,799,788	288
2,799,821	68
2,799,842	16
2,799,855	316
2,799,856	316
2,799,946[a]	44
2,800,016	148
2,800,017	148
2,800,018	148
2,800,019	148
2,800,020	148
2,800,024	16
2,800,025	16, 180, 232
2,800,100	12, 484

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	Subject*
2,800,276	68
2,800,277	68
2,800,278	68
2,800,279	68
2,800,309	12, 484
2,800,384	324
2,800,397	168
2,800,460	168
2,800,523	40
2,800,534	224
2,800,583[a]	352
2,800,591	308
2,800,610	12
2,800,629[a]	124
2,800,633	12
2,800,639[a]	352
2,800,642	224
2,800,648	200
2;800,651	312
2,800,653	312
2,800,654	316
2,800,723	216
2,800,789	12, 140
2,800,790	428, 324
2,800,794	148
2,800,796	288
2,800,972[a]	490
2,801,051	16
2,801,052	68
2,801,097	4
2,801,148	108, 324
2,801,293	224
2,801,294	484
2,801,387	288
2,801,403	12, 108
2,801,410[a]	124
2,801,538	188
2,801,539	428
2,801,542	16
2,801,543	16
2,801,544	16, 180, 232
2,801,794[a]	180, 68
2,801,795	68
2,801,816	16
2,801,905	168
2,802,053	12
2,802,054	484
2,802,109	168
2,802,112	308
2,802,113	308
2,802,138	68
2,802,172[a]	88
2,802,173[a]	88
2,802,196	484
2,802,201	324
2,802,272	68
2,802,279	16
2,802,290	224
2,802,362	200
2,802,363	200
2,802,364	16
2,802,389	444
2,802,421	136
2,802,422	136
2,802,624	68
2,802,625	68
2,802,905	484, 224
2,802,951[a]	516, 304
2,803,001[a]	360
2,803,068	216
2,803,134	428
2,803,135	288
2,803,161	440
2,803,341	140
2,803,399	68
2,803,415	312
2,803,515[a]	364
2,803,526[a]	508, 452
2,803,708	224
2,803,709	224
2,803,713	484
2,803,755	140
2,803,760	428
2,803,762	484
2,803,794	16
2,803,796[a]	116
2,803,798[a]	232
2,803,801[a]	12, 352
2,803,807	436
2,803,808	484
2,803,809[a]	368
2,803,815	68
2,803,819	316
2,803,820	68, 316
2,803,821	312
2,803,887	16
2,803,960	412
2,803,962	148
2,803,988	224
2,803,992	444
2,804,042	12, 484
2,804,366	324
2,804,401	224
2,804,506	484
2,804,509[a]	484, 376
2,804,517	200
2,804,549	420
2,804,593	188
2,804,603[a]	376
2,804,605	224
2,804,613	316
2,804,615	312
2,804,616	312

REVIEWS

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CONTENTS

Elastic Waves in Layered Media, W. Maurice Ewing, Wenceslas S. Jardetsky, and Frank Press, by *J. E. White* 172
Glossary of Geology and Related Sciences, American Geological Institute, by *W. T. Born* 173
IGY Rocket Program, Subcommittee for IGY of the Technical Panel for Rocketry, by *Franklyn K. Levin* 173
Potential Hazard of RF Energy to Electric Blasting, Pamphlet No. 20, Institute of Makers of Explosives, by *Elmer Johnson* 174
Seismic Model Studies Part 1, on Rayleigh Waves, Takagi, Akio 174
Science Model Studies Part 2, On Dilatational and Distortional Waves in Semi-infinite Solid Due to a Linear Surface Impulse, Takagi, Akio 174
Model Seismology Part 3, Wave Propagation in the Step-shaped Structure and on the Cliff, Kato, Yoshi, and Takagi, Akio, by *Franklyn K. Levin* 174

Elastic Waves in Layered Media, W. Maurice Ewing, Wenceslas S. Jardetzky, and Frank Press, McGraw-Hill Book Company, Inc., New York, New York, 380 pp., 1957. $10.00.

This scholarly and comprehensive work provides a unified treatment of a phase of geophysical theory which has contributed greatly to our understanding of earthquake seismology and geophysical prospecting. Beginning with a derivation of the elastic wave equation and a statement of its most general solution, the authors proceed with a discussion of the effect of a single plane boundary, a treatment of two media in contact along a plane, and, in thorough detail, a presentation of the theory for a medium containing one or more layers. The authors cover a tremendous range of subject matter at a pace which presupposes on the part of the reader some familiarity with elastic waves and an adequate mathematical background. Although the derivations proceed without much introduction or elaboration, there are numerous ray diagrams and qualitative summaries which help to clarify the final results. In many cases, results are presented as dispersion curves, that is, relations between phase or group velocity and frequency for sinusoidal excitation. Many features of the transient behavior can be inferred from these curves. In several cases, the waveforms due to impulsive excitation at a point were derived directly. Although discussions of experimental work comprise a very small fraction of the total book, there are some elegant comparisons between appropriate theories and results from earthquake seismology, seismic prospecting, and model work.

A major contribution of this book is the comprehensive bibliography of the world literature which has been compiled for the main topics and the guiding comments in the text as to the signicance of many references. In selecting from the literature topics to be treated in detail in the text, the authors have justly drawn heavily from their many recent publications concerning both theoretical and experimental aspects of wave propagation in layered media.

For completeness, a chapter was devoted to the effects of gravity, curvature, and viscosity;

another to propagation in plates and cylinders; and a third to media with continuously variable properties. This last chapter includes a discussion of propagation along the well-known SOFAR channel.

Beyond question, this book will take its place as a classic reference work in elastic wave theory and will serve as a valuable guide to persons delving deeply into this field.

J. E. WHITE

Glossary of Geology and Related Sciences, American Geological Institute, Washington, D. C., 325 pp., 1957, $6.00.

Some six years of planning and preparation preceded the publication of this comprehensive and authoritative glossary. It is a publication of the American Geological Institute, made possible by financial assistance from the National Science Foundation and the Geological Society of America. The planning and compilation of the work was done by a Steering Committee under the Chairmanship of J. V. Howell, the S.E.G. being represented by Richard A. Geyer. Selection of definitions was made by sub-committees made up of specialists in all fields of geology and geophysics. Here the S.E.G. was again well represented by a group of eminent geophysicists under the chairmanship of Paul L. Lyons. Included in the group were E. A. Eckhardt, Sigmund I. Hammer, T. A. Elkins, L. L. Nettleton, and Henry Faul.

The Glossary contains some fourteen thousand entries covering all fields of geology and geophysics, except the field of Vertebrate Paleontology. In addition to formal terminology, the entries include many colloquial expressions, e.g., "jug."

The pressing need for an authoritative glossary in the field of earth science is evidenced by the fact that this Glossary had a sale of over five thousand copies within three months of publication. It will undoubtedly prove a valuable addition to the library of every geologist and geophysicist.

Probably because of limited publication funds, the Glossary is printed by the photo-offset process through reduction from typewritten copy. With the success of this edition already assured, it is to be hoped that a second edition may soon appear in a better format.

This reviewer would like to extend his personal thanks to Mr. Howell and all the others who made this work possible. It is a lasting, valuable contribution to all who work in the many fields of earth science.

W. T. BORN

IGY Rocket Program, Subcommittee for IGY of the Technical Panel for Rocketry, *The Scientific Monthly*, Vol. 85, pp. 130–142, Sept., 1957.

From July, 1957, until the end of 1958, the United States will launch about two hundred rockets, some capable of reaching nearly three hundred kilometers. The rockets, probing directly the further reaches of the earth's atmosphere, will represent a major contribution of this country to the International Geophysical Year.

While upper atmospheric investigations probably are not of immediate interest to members of this society, the scientific problems being attacked are fascinating in themselves and some, particularly those of sound propagation, similar to problems met in theoretical seismology. In the present paper the subcommittee concerned with rocket studies gives a nontechnical account of the proposed experiments and equipment.

Two types of rocket vehicles will be used: relatively large, self-contained Aerobees and balloon or Jato-launched smaller rockets. The Aerobees will be fired at Fort Churchill in Canada and at the New Mexico proving grounds; the smaller units, from many points around the earth. Information sought will be density, temperature, pressure, wind movements, and water vapor content of the earth's atmosphere and details of solar related constituents such as ozone and of solar emanations.

There is not space here even to summarize this excellent paper. The reviewer would like to mention two planned experiments he found beautiful in their simplicity and ingenuity. A group from the U. S. Army Signal Engineering Laboratories will measure temperatures and winds by recording the arrival times of sounds from grenades ejected periodically as an Aerobee ascends. The

grenades are to be exploded at known times and altitudes. The second experiment, this by the University of Michigan's aeronautical engineering department, will give air density from the telemetered deceleration of a 7 inch sphere released at high altitude. As in well logging, simple tools are best and complex equipment does not ensure maximum information. It may mean merely high cost and no information at all.

FRANKLYN K. LEVIN

Potential Hazard of RF Energy to Electric Blasting, Pamphlet No. 20, Institute of Makers of Explosives, 250 East 43rd Street, New York 17, New York. No charge.

Many years of experience and numerous tests have indicated that the hazard of radio frequency energy to blasting operations has been greatly exaggerated, according to a booklet recently published by the Institute of Makers of Explosives.

Pamphlet No. 20 entitled "Radio Frequency Energy a Potential Hazard in the Use and Transportation of Electric Blasting Caps," explains how RF energy can fire an electric blasting cap and what precautions should be taken to minimize this hazard. The tables of distances for safe electric blasting operations from fixed or mobile transmitters, particularly those for the FM mobile transmitters, are quite revealing.

Pamphlet No. 20 is available from the Institute of Makers of Explosives, 250 East 43rd Street, New York 17, New York, or from most of its member companies.

ELMER JOHNSON, Chairman
S.E.G. Committee on Safety

Seismic Model Studies Part 1, On Rayleigh Wave, Takagi, Akio, *The Science Reports of the Tohoku University, Geophysics*, Vol. 8, pp. 64–68, 1956.

Science Model Studies Part 2, On Dilatational and Distortional Waves in Semi-infinite Solid Due to a Linear Surface Impulse, Takagi, Akio, *The Science Reports of the Tohoku University, Geophysics*, Vol. 8, pp. 69–73, 1956.

Model Seismology Part 3, Wave Propagation in the Step-shaped Structure and on the Cliff, Kato, Yoshi, and Takagi, Akio, *The Science Reports of the Tohoku University, Geophysics*, Vol. 8, pp. 74–85, 1956.

The three papers reviewed here are the second contribution of Professor Takagi and his co-workers to the growing literature of seismic model studies. As in the previous work of the Tohoku University group, two-dimensional models were used exclusively, with the emphasis being on the propagation of *P*, *S*, and Rayleigh pulses in simple geometries.

The first paper of this set reports still another investigation of the Lamb problem, the source this time being a crystal disk transducer in a grease-filled hole. To the present reviewer's knowledge, this technique is new, although Clay did similar (unpublished) experiments in 1954, and Sherwood has developed a different method of studying the interior of two-dimensional models. In the second paper, the amplitudes of *P* and *S* waves generated by a surface impulse are compared with the predictions of Honda, Nakamura, and Takagi. The agreement of theory with experiment is excellent for the *P* wave, fair for the *S* wave.

Readers of GEOPHYSICS will find the third paper most interesting. Secondary generation of Rayleigh waves by surface irregularities doubtlessly contributes to the complexity of seismograms. Such secondary waves appear on the model records from a step. Kato and Takagi identify not only *P* to Rayleigh wave conversions but also Rayleigh wave to Rayleigh wave events. In this study, both buried disk and surface incident sources were used. The identification would have been clearer if the arrivals had been labeled on the photographs as well as on the time-distance plots. A variation of the step geometry, that of a corner, is described also. Again the two types of conversions were found.

The importance of the problems considered by the Tohoku University group and the ingenious techniques they have devised promise papers of increasing interest in the future.

FRANKLYN K. LEVIN

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Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 9, nos. 1–2, 5–6 (1957)
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Bulletin of the Seismological Society of America, v. 47, nos. 3 & 4 (July & October, 1957)
Department of Mines South Australia, Geological Survey, *Mining Review*, nos. 99 & 100 (1953 & 1954)
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Scientific Monthly, v. 84, nos. 5 & 6 (May & June, 1957); v. 85, nos. 1, 2, 3, & 4 (July–October, 1957)
South Australia Department of Mines, Mining Review, n. 102 (1957)
Soviet Physics JETP, v. 4, n. 6 (July, 1957); v. 5, nos. 1 & 2 (August & September, 1957)
Transactions American Geophysical Union, v. 38, n. 4 (August, 1957)

MISCELLANEOUS BOOKLETS AND PAMPHLETS

Commonwealth of Australia, Department of Natural Development, Bureau of Mineral Resources, Geology and Geophysics.
Bulletin No. 31. DALY, J., URQUHART, D. F., and GIBSON, M. R., "Assaying of Radioactive Rocks and Ores." (1956)
Bulletin No. 35. URQUHART, D. F., "The Investigation of Deep Leads by the Seismic Refraction Method."

Disaster Prevention Research Institute, Kyoto University. Bulletin No. 15. OZAWA, IZUO, "Study on Elastic Strain of the Ground in Earth Tides." (March, 1957)
Bulletin No. 16. YOKOO, Y., and TSUNODA, S., "Consideration on Mechanism of Structural Cracking of Reinforced Concrete Buildings Due to Concrete Shrinkage." (March, 1957)
Bulletin No. 17. AKAI, K., "On the Stress Analysis and the Stability Computation of Earth Embankments." (March, 1957)
Bulletin No. 18. ISHIZAKI, H., "On the Numerical Solutions of Harmonic, Biharmonic and

Similar Equations by the Difference Method not through Successive Approximations." (August, 1957)

Annual Report of the Director of Mines and Government Geologist for 1955 with Appendix. Adelaide, South Australia: Government Printer, 1956.

Bi-annual Report (1955–1956) of the Mexican Scientific and Technical Documentation center. Secretary of Public Education. Mexico City: Centro de Documentacion Cientifica y Tecnica de Mexico, 1957.

Salzer, Herbert E., and Roberson, Peggy T. *Table of Coefficients for Obtaining the Second Derivative without Differences*. San Diego: Convair-Astronautics, 1957.

MEMORIAL

WESTON CAWTHORNE KIMBALL

WESTON CAWTHORNE KIMBALL died on September 21, 1957, at his home in Houston, Texas, after an illness of several months.

"Kim" was born in Green Bay, Wisconsin, on October 8, 1903. He attended the University of Wisconsin from 1922 to 1926 where he was a member of Beta Theta Pi. While at the university his association with Gordon Taylor, one of the pioneers in seismic exploration, led to Kim's selection of geophysics as a career. He joined Taylor's company, the Geophysical Exploration Company and worked in various capacities, eventually becoming party chief of a refraction crew operating in South Texas and South Louisiana. While stationed in Angleton, Texas, Kim met and subsequently married in September, 1929, Katherine Bennett, who survives him together with three children, Mrs. Robert Martin III, Weston C. Kimball, and Charles Theodore Kimball, and two grandchildren.

In the latter part of 1931, the Geophysical Exploration Company sold its mechanical seismographs to the Continental Oil Company, and Kim served in an advisory capacity with Conoco for several months.

After his return to Texas, Kim joined The Texas Company in December, 1932, in the geophysical department. He later became a party chief and then supervisor for the South Texas division. In 1947 he joined the Apache Exploration Company in an administrative and supervisory capacity. In 1951 he became a vice-president and in 1952 a member of its Board of Directors.

During his association with the various phases of seismic work, Kim maintained his keen interest in interpretation and spent much of his time in this field. The discoveries based on his work are a

testimony to his ability. His quality of leadership through example, enhanced by his outstanding personality, made people willing and eager to perform with him and for him.

No eulogy of Kim would be complete without reference to his sense of humor and his love of fun. He possessed the unique ability to work hard while he was working, to play hard while he was playing, and to recognize the proper time for each. His "ribbing," his humor, his kindly nature, and the spark of devilment in his eyes will always be remembered by those who were privileged to know him. His many, many friends will agree that life was more pleasant because Kim was there.

A. L. LADNER

HOUSTON, TEXAS
September 24, 1957

CONTRIBUTORS

ALBERT W. MUSGRAVE

ALBERT W. MUSGRAVE was born in 1923 at Eads, Colorado. He spent two years in the Navy as a radio technician before his graduation from the Colorado School of Mines in 1947 with a degree in geological engineering (geophysics option). After spending three years on a field seismic crew with the Magnolia Petroleum Company, where he advanced to the position of seismologist, he returned to the Colorado School of Mines for advanced work. On a Magnolia Fellowship he obtained the degree of Doctor of Science in geophysics in 1952 and returned to work with the Magnolia Petroleum Company as a seismic party chief. His thesis "Wavefront Charts and Raypath Plotters," was later published as a quarterly of the Colorado School of Mines. In 1954 he was made research geophysicist attached to the Dallas office of the Magnolia Petroleum Company. His work consists of applied research on special seismic problems in velocity surveying, refraction profiling, and reflection interpretation.

Dr. Musgrave is a member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists, the European Association of Exploration Geophysicists, the Tau Beta Pi Society, and the Scientific Research Society of America. In 1957 he was second vice-president of the Dallas Geophysical Society and a member of the Joint Geological and Geophysical Committee on Public Information.

D. M. NASH, JR.

D. M. NASH, JR. was born in Dallas, Texas, in 1926. He served as a radio officer with the U. S. Navy during World War II. After the wartime interruption he completed his college training in 1948, and from the University of Texas he received the degree of B.S. in Electrical Engineering.

Upon his graduation he was employed by the Magnolia Petroleum Company to work in their geophysical department. After he advanced to the rank of seismic party chief, he was transferred to the Socony Mobil Oil Company, Inc., for a brief period. He was afterwards assigned to the geophysical laboratory of the Magnolia Petroleum Company for three years before he was given his present position as a geophysicist in its West Texas district at Midland.

Mr. Nash is a member of the Society of Exploration Geophysicists.

JOHN I. BRUSTAD

JOHN I. BRUSTAD was born in Minot, North Dakota. In 1942 he received the degree of B.S. in Chemical Engineering from the University of North Dakota.

After two years of association with the U. S. Rubber Company in the production of TNT, he joined the U. S. Army and saw duty in the Pacific Theater.

After his discharge from the service he located in California. There he worked for the Richfield Oil Company for three years. Upon receiving a master's degree in mathematics from the University of Southern California in 1951 he joined the Western Geophysical Company of America as a staff mathematician.

Early in 1957 he joined the Convair corporation to work in the guided missile field.

He is a member of the Society of Exploration Geophysicists and of its Pacific Coast Section.

WILLIAM C. DEAN received his B.S. degree in 1949 from the Carnegie Institute of Technology and his M.S. in Electrical Engineering from the same institution in 1950. In 1951 and 1952 he held a research fellowship there and was engaged in research on gaseous conduction phenomena in thyratrons for which he was awarded the Ph.D. in 1952.

From 1952 to the present he has been employed by the Gulf Research and Development Company as a research geophysicist.

Dr. Dean is a member of the Society of Exploration Geophysicists, the Institute of Radio Engineers, Sigma Xi, and Eta Kappa Nu.

WILLIAM C. DEAN

GILBERT W. EHLERT, a native of Texas, entered the School of Engineering of the University of Texas in 1940.

There he completed two years of study before he joined the Signal Corps of the U. S. Army. In his tour of duty he served as a radio repairman, teletype operator, and instructor in teletype operation. After his discharge from the service he resumed his studies at the University of Texas, and in 1948 he received the degree of B.S. in Mechanical Engineering.

Since his graduation he has been employed in the geophysical department of the Magnolia Petroleum Company. He is now a seismic party chief doing experimental field work.

Mr. Ehlert is a member of the Society of Exploration Geophysicists.

GILBERT W. EHLERT

W. A. KNOX

W. A. KNOX was educated for the priesthood at St. Anthony's Seminary, Santa Barbara, California.

During World War II he served in the U. S. Army Air Forces, and he became chief navigation officer of the Thirteenth Bomber Command in the South Pacific Theater.

In 1946 he joined the Western Geophysical Company, and he is now a vice-president of the Western Geophysical Company of Canada, Ltd.

He is a member of the Society of Exploration Geophysicists, the American Geophysical Union, and the American Association for the Advancement of Science.

EDWIN B. NEITZEL

EDWIN B. NEITZEL received the degree of B.S. in Electrical Engineering with high honors from Southern Methodist University in 1950 and the degree of M.S. in Electrical Engineering from the University of Texas in 1952. From 1951 to 1952 he was employed as a research engineer at the Electrical Engineering Research Laboratory of the University of Texas.

Since 1946, except for the time at the University of Texas, he has been employed on either a part time or a full time basis by The Atlantic Refining Company. From 1946 to 1951 he held various positions in field seismic exploration. Since 1952 he has been an electrical engineer with the Atlantic geophysical laboratory. During this time he has worked on electrical prospecting, experimental studies of seismic signal detection, weight dropping seismic methods, and special purpose seismic computers.

He is a member of the Institute of Radio Engineers, the IRE Professional Group on Audio, the Society of Exploration Geophysicists, the American Geophysical Union, the Dallas Geophysical Society, Kappa Mu Epsilon, and Sigma Tau.

CARL H. SAVIT

CARL H. SAVIT was born in New York City in 1922. He did his undergraduate work in mathematics and physics at the California Institute of Technology, and he was a graduate student and teaching fellow there for four years.

Mr. Savit has done research in statistics, statistical meteorology, and upper atmosphere physics.

He was with the U. S. Army Air Forces for two years and was stationed for duty as a project officer at Wright Field, Ohio, and Alamogordo, New Mexico, working principally in upper atmosphere physics.

Mr. Savit is presently the chief mathematician of the Western Geophysical Company with which he has been associated since 1948. He is a member of the Society of Exploration Geophysicists, the European Association of Exploration Geophysicists, the American Mathematical Society, the Mathematical Association of America, and the Society of Sigma Xi. In SEG he has served as vice-president of the Pacific Coast Section and chairman of the Distinguished Lectures Committee; and he is now a member of the Reviews Committees of SEG.

JOESPH SIDER

JOSEPH SIDER was born in New York City on May 9, 1927. He received the B.S. degree in mathematics in 1949 from the University of Denver following a period with the Navy as a radar technician and as a student at the College of the City of New York. In 1952 he received the M.S. degree in mathematics from the University of California at Berkeley.

During 1952–1953 Mr. Sider served as aeronautical research scientist with the National Advisory Committee on Aeronautics at Edwards Air Force Base. He was associated with the Western Geophysical Company at Los Angeles from 1953 to 1955 as staff mathematician. Since 1955 Mr. Sider has been with the International Business Machines Corporation as an applied science representative.

JAMES PAUL WESLEY

JAMES PAUL WESLEY was born in 1921. He received the B.A. degree in 1943 from the University of Minnesota, the M.A. in 1949 from the University of California at Los Angeles, and in 1952 the Ph.D. in mathematical physics from the latter university. He completed his doctoral thesis on electromagnetic radiation from a coaxial antenna while he was a research fellow at the Institute for Numerical Analysis, NBS.

He spent the year 1951–1952 as a research fellow in physics at the Scripps Institution of Oceanography working on the Sommerfeld problem of dipole radiation in a half space. He was a professor of physics at the University of Idaho for three years (1952–1955). He spent the summer of 1954 at the Institute of Geophysics at the University of California at Los Angeles. As a consultant he became interested in the problems of electromagnetic geophysical exploration. In 1955 he worked for Newmont Exploration Limited. Since that time he has been a theoretical physicist with the University of California Radiation Laboratory at Livermore.

Biographies and photographs of the following authors appear in earlier issues of GEOPHYSICS as follows: Haro von Buttlar, v. 22, pp. 735–736; Richard H. Frische, v. 22, p. 732; Mark K. Smith, v. 21, p. 509; James R. Wait, v. 21, pp. 509–510; J. E. White, v. 18, p. 244.

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN OCTOBER 1958

Executive Committee

President: O. C. Clifford, Jr., The Atlantic Refining Co., Dallas, Texas
Vice-President: Ben F. Rummerfield, Century Geophysical Corp., Tulsa, Oklahoma
Secretary-Treasurer: Howard E. Itten, Empire Geophysical Inc., Ft. Worth, Texas
Editor: Lawrence Y. Faust, Amerada Petroleum Corp., Tulsa, Oklahoma
Past President: Roy F. Bennett, Sohio Petroleum Co., Oklahoma City, Oklahoma

Nominations

O. C. Clifford, Jr., *Chairman*
Roy F. Bennett
R. C. Dunlap, Jr.

Tellers

To be appointed.

Education

Joshua L. Soske, *Chairman*
Victor J. Blum, S.J.
P. E. Dehlinger
G. D. Garland
J. W. Hoover
J. B. Hudson
V. Vacquier

Student Membership

W. H. Courtier, *Chairman*

Distinguished Lectures

John Bemrose ('59)
Milton Born ('59)
M. E. Denson, Jr. ('58)
R. A. Peterson ('58)

Radio Facilities

B. D. Lee, *Chairman*
W. M. Rust, Jr., *Vice-Chairman*
C. B. Bazzoni
Richard Brewer
V. Robert Kerr
E. M. Shook
Daniel Silverman
Bart W. Sorge

Membership

John C. Hollister, *Chairman*

Honors and Awards

Sigmund Hammer ('58) *Chairman*
Curtis H. Johnson ('59)
Roy L. Lay ('60)
Paul L. Lyons ('61)

Publications

Cecil H. Green, *Chairman*
Henry C. Cortes
Sigmund I. Hammer
H. B. Peacock
Robert J. Watson

Reviews

Franklyn K. Levin, *Chairman*
W. T. Born
Thomas A. Elkins
W. W. Garvin
Sigmund I. Hammer
Chwan-Chang Lee
John E. Nafe
Carl H. Savit
V. Vacquier
James E. White

Geophysical Activity

H. G. Patrick, *Chairman*
Kenneth L. Cook
R. J. Copeland
W. W. Hardy
Herbert Hoover, Jr.
Santos Figueroa Huerta
C. N. Hurry
Kumiji Iida
C. C. Lister

Safety

To be appointed.

Mining Geophysics

Ralph C. Holmer, *Chairman*
Kenneth L. Cook
H. V. W. Donohoo
Walter E. Heinrichs, Jr.
LeRoy Scharon
R. Maurice Tripp
Stanley H. Ward

Case Histories

To be appointed.

Constitution and Bylaws

W. M. Rust, Jr., *Chairman*
Henry C. Cortes
Andrew Gilmour
Cecil H. Green
Sigmund Hammer
J. J. Jakosky
L. L. Nettleton

Membership in American Institute of Physics

Norman H. Ricker, Liaison Member

Research

W. T. Born, *Chairman*

Research Subcommittee on University Symposia

To be appointed.

Research Subcommittee on Thesis Subjects

To be appointed.

Research Advisory Committee on Rice Institute Symposium

To be appointed.

Index of Wells

V. U. Gaither, *Chairman*

Magnetic Recording

J. D. Skelton, *Chairman*
Keith R. Beeman
Roland F. Beers
K. E. Burg
J. D. Eisler
Glenn M. Grosjean
J. E. Hawkins
K. M. Lawrence
B. D. Lee
G. B. Loper
R. A. Peterson
E. B. Tickell
F. A. Van Melle

Magnetic Recording Subcommittee on Definitions & Measurement

L. W. Erath, *Chairman*
R. A. Arnett
Frank Coker
J. M. Cunningham
J. J. Durapau
F. J. Feagin
H. R. Frank
Roger Harlan
R. W. Kelley
L. B. McManis
R. C. Moody

Magnetic Recording Subcommittee on Recorder Characteristics

S. KAUFMAN, *Chairman*
A. L. PARRACK

American Geological Institute Directors

R. C. DUNLAP, JR. ('58)
ROY F. BENNETT ('59)

AGI Glossary

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D. S. HUGHES
PAUL L. LYONS
L. L. NETTLETON
D. C. SKEELS
I. A. VAN WEELDEN
J. TUZO WILSON

AGI Committee on Licensing

A. E. MCKAY, SEG MEMBER

Business Office

CRAIG FERRIS, *Chairman*
JAMES F. JOHNSON

National Research Council Div'n of Earth Sciences Representative

R. D. WYCKOFF

AAAS Council Representative

ROLAND F. BEERS

Radioactive Mineral Exploration

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A. J. HINTZE
JOHN C. HOLLISTER
F. H. LAHEE
PAUL L. LYONS
L. W. MACNAUGHTON
JOHN MASTERS
A. GARCIA ROJAS
STAN. L. ROSE

SEG Committee on IGY

PAUL L. LYONS, *Chairman*

Publicity and Public Relations

BART W. SORGE, *Chairman*

Sustaining Membership

L. O. SEAMAN, *Chairman*

LOCAL SECTIONS

Geophysical Society of Tulsa

Chartered February 2, 1948
Frank Searcy, *pres.*
T. S. Green, *1st v-pres.*
F. R. Kittredge, *2nd v-pres.*
P. M. McNally, *treas.*
R. L. Frossard, *editor*
S. E. Giulio, *secty.* The Carter Oil Co., Box 801, Tulsa 2, Okla.
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, room 224, Petroleum Science Hall

Houston Geophysical Society

Chartered February 14, 1948
G. P. Montgomery, Jr., *pres.*
J. M. Wilson, *1st v-pres.*
C. C. Sellers, *2nd v-pres.*
J. P. Pascall, *treas.*
E. J. Marti, *secty.* Union Oil Co. of Calif., 800 Prudential Bldg., Houston, Texas
Meetings: Monthly, Noon luncheon ($1.65), Rice Hotel

Pacific Coast Section SEG

Chartered April 12, 1948
Flint H. Agee, *pres.*
C. A. Bengston, *v-pres., N.D.*
Lawrence S. Morrison, *v-pres., S.D.*
F. E. Schultz, *v-pres., S.D.*
William L. Basham, *secty.* Std. Oil Co. of Calif., 325 W. 9th St., Los Angeles, Calif.
Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles

Dallas Geophysical Society

Chartered August 7, 1948
R. E. Rettger, *pres.*
Chester Donnally, *1st v-pres.*
A. W. Musgrave, *2nd v-pres.*
Wm. C. Wooley, *secty.* Magnolia Petroleum Co., Box 900, Dallas, Texas
Meetings: Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Building, Southern Methodist University

Fort Worth Geophysical Society

Chartered August 7, 1948
C. J. Long, *pres.*
O. A. Strange, *v-pres.*
D. T. McCreary, *secty.* The Texas Co., Box 1720, Fort Worth, Texas
Meetings: Monthly, 4th Monday, Noon luncheon ($1.50), Texas Hotel

Ark-La-Tex Geophysical Society

Chartered March 12, 1949
C. P. Bragg, *pres.*
Bill C. Tucker, *v-pres.*
S. T. Spradlin, *secty.* The Ohio Oil Company, P.O. Box 1129, Shreveport•Louisiana
Meetings: Monthly, last Monday, Noon luncheon ($1.50), Captain Shreve Hotel, Shreveport

Permian Basin Geophysical Society

Chartered January 30, 1950
R. M. Pinson, *pres.*
B. F. Owings, *1st v-pres.*
E. E. Fickinger, *2nd v-pres.*
B. A. Heidt, *treas.*
J. E. Clark, *secty.* Box 1018, Midland, Texas
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee & donuts, Midland Women's Club, Midland, Texas

Denver Geophysical Society

Chartered May 19, 1950
R. C. Kendall, *pres.*
J. E. Thompson, *v-pres.*
C. B. Smith, Jr., *secty.* Continental Oil Co., 3571 Grape St., Denver, Colo.
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only. Petroleum Club, Denver

Canadian SEG

Chartered January 24, 1952
George J. Blundun, *pres.*
John Fuller, *v-pres.*
Lorne H. Reed, *secty.* Universal Seismic Surveys, Ltd., 223 14th St. N.W., Calgary, Alberta
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City

Chartered September 30, 1952
W. B. Robinson, *pres.*
G. E. Anderson, *1st v-pres.*
R. H. Peacock, *2nd v-pres.*
C. L. Howell, *treas.*
H. R. DeVinna, *secty.* Central Exploration Co., 13 NE 28th, Okla. City, Okla.
Meetings: Monthly, 2nd or 3rd Monday. Time and place to be announced

Casper Geophysical Society

Chartered May 23, 1953
Dupree McGrady, *pres.*
A. C. Austin, *v-pres.*
R. L. Billings, *secty.* Forest Oil Corp., 254 N. Center St., Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming

Geophysical Society of South Texas

Chartered November 9, 1953
Wm. R. Gray, *pres.*
Wm. Harry Mayne, *v-pres.*
Jack W. E. Edmonson, *secty-treas.* 713 First Nat'l Bank Bldg., San Antonio 5, Texas
Meetings: 1st and 3rd Wednesdays, Noon luncheon, Sommers Cafeteria, Main Plaza, San Antonio

Southeastern Geophysical Society

Chartered April 1, 1954
Merrill Smith, *pres.*
Wm. G. Hazen, *v-pres.*
G. F. Berry, *secty.* 203 Carondelet Bldg., New Orleans, Louisiana
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans

Montana Geophysical Society

Chartered April 12, 1954
Jack W. Peters, *pres.*
C. F. Moore, Jr., *1st v-pres.*
Phillip I. Hendricks, *2nd v-pres.*
Ward T. Langstroth, *secty-treas.* The Carter Oil Co., Box 1982. Billings, Montana
Meetings: Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club

Jackson Geophysical Society

Chartered May 12, 1955
W. J. Robinson, *pres.*
R. C. Cole, *v-pres.*
J. E. MacGregor, *secty.* The California Company, Box 2606, Jackson, Mississippi.
Meetings: Monthly, during 3rd week, 5:30 P.M., refreshments, 6:30 P.M., dinner ($2.00), Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi

Southwest Louisiana Geophysical Society

Chartered January 4, 1956
John W. Bell, Jr., *pres.*
A. V. Hargis, *1st v-pres.*
W. W. Daly, *2nd v-pres.*
Lawrence N. Ott, *secty.* Tidewater Oil Co., Box 1147, OCS, Lafayette, Louisiana
Meetings: to be announced

Utah Geophysical Society

Chartered October 29, 1956
J. R. Cheney, *pres.*
R. J. Lacy, *1st v-pres.*
D. E. Smith, *2nd v-pres.*
E. W. Morris, *secty.* General Petroleum Corporation, 53 East 4th South, Salt Lake City, Utah

Dakota Geophysical Society

To be chartered
W. E. Phillips, *pres.*
Hugh McCain, *1st v-pres.*
Quin Hayes, *2nd v-pres.*
R. R. Phair, *secty.* Roundup Powder Company, Box 452, Bismarck, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck, North Dakota

New Mexico Geophysical Society

Chartered September 18, 1957
J. C. Eley, *pres.*
F. A. Grimm, *1st v-pres.*
W. P. Scaife, *2nd v-pres.*
R. V. Smith, *secty.* Shell Oil Company, 905 South Plains Park Drive, Roswell, New Mexico

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists

Ernest Berkman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University

Wm. Reeves, *secty.* Saint Louis University, 3621 Olive Street, St. Louis 8, Missouri
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section

Reed B. Kubena, *secty.* Box 6527, Houston, Texas
Meetings: to be announced

University of Toronto Geophysical Society

John E. Hogg, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society

Hugh Hayes, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section

John T. Sample, Jr., *secty.* Box 56, Texas Western College, El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society

Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society

Howard L. Confer, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday, Noon, Mines Building. Other special meetings to be announced

A & M College of Texas Student Geophysical Society

Edward C. Hanson III, *secty* Geology and geophysics dept., A & M College of Texas, College Station, Texas

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

H. H. Bradfield (A. A. Hunzicker, Holland C. McCarver, Roy L. Lay, T. L. Kunkel)
Ben F. Ehrlich (J. R. Ording, Derry H. Gardner, R. R. Thompson)
Sheldon E. Elliott (J. E. Bondurant, R. G. Piety, Ralph C. Loring)
Gerald D. Fawcett (Maurice Sklar, John Sloat, Willard Strangman, Donald L. Olson)
Arthur M. Field (J. S. Page, J. A. Lester, R. M. Nugent, A. W. Musgrave)
G. W. Guiling (Maxey Pinson, Leorenz Shock, B. F. Owings, J. E. Clark)
S. S. Rajsfus (Raoul Giret, W. B. Agocs, Vladimir Baranov, David J. Leeds)
M. L. Randall (W. J. Osterhoudt, Sidney Schafer, J. R. Schander, B. W. Walton)
A. T. Roux (Oscar Weiss, G. L. Paver, J. F. Enslin, J. W. N. Sharpe)
Juan I. Spescha (Rodolfo A. Hernandez, Eufrasio Orellana, Metello Cesanelli, E. L. Cebrelli)
Ira H. Stein (Howard Itten, J. A. Cubertson, Tom Lawhorn, Sidney Schaffer)
John D. Storm (John P. Lukens, G. D. Gibson, D. F. Smith, Kenneth McDonald)
S. H. Van Wambeck (A. A. Hunzicker, John D. Marr, F. F. Reynolds, T. F. Dupont, Jr.)
T. B. White (O. C. Clifford, Jr. Richard Brewer, John T. Murphy, Jr. Hugh McCain, Jr.)
Robert J. Zavadil (W. H. Murphy, C. P. Felix, Oris D. Massey, Roy G. Quay)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

Joy J. Anneler (Miller W. Quarles, Jr., Hrebert Schlundt, E. E. Conant)
J. A. Hudson (M. B. Dobrin, J. C. Hoffman, T. A. Halbrook)
Alfred E. LaPointe (G. A. Burton, G. H. Samuels, L. B. Stumpf)
Carl D. McKeever (L. G. Ellis, R. H. Hopkins, G. M. Conklin)
Kenneth W. Paul (George T. Meredith, M. King Hubbert, H. E. Stommel)
James R. Root (J. C. Baxter, S. O. Patterson, Nash Miller)
E. W. Rosen (R. H. Rainey, C. M. Moore, Jr., R. D. Everett)

ANNOUNCEMENTS

ELEVENTH MIDWESTERN EXPLORATION MEETING

The Geophysical Society of Tulsa and the Tulsa Geological Society will be co-hosts in sponsoring the Eleventh Midwestern Exploration Meeting of the Society of Exploration Geophysicists to be held in Tulsa, Oklahoma, on April 17 and 18, 1958.

The Central Steering Committee will be:

W. M. Erdahl, Skelly Oil Co., General Chairman
James L. Martin, Jr., Sinclair Oil and Gas Co., Co-chairman
James F. Johnson, Sinclair Research Laboratories, Inc., Program Chairman
C. W. Alcock, Atlantic Refining Co., Program Co-chairman
Frank E. Brown, Republic Exploration Co., Arrangements Chairman
R. D. Faxon, Keener Oil Co., Arrangements Co-chairman
E. H. Weltsch, Century Geophysical Corp., Finance Chairman
Harry True, Schlumberger Well Surveying Corp., Finance Co-chairman

The theme of the meeting will be *Stratigraphic Traps*. The Technical Program Committee earnestly requests that any persons having papers to present at this meeting submit their titles and abstracts promptly to the committeeman in the author's area so that the complete program can be closed on February 28, 1958, as a final deadline. Let it also be emphasized that papers need not be confined to the general theme of the meeting. Papers on the theoretical or experimental phases of geophysics are especially welcome, for communications of this type are depended upon for publication in this journal.

The Technical Program Committee is composed of:

Norman Ricker, Carter Oil Co., Box 801, Tulsa, Okla., Chairman
H. F. Dunlap, Atlantic Refining Co., Box 2819, Dallas, Tex.
Sidon Harris, Southern Geophysical Co., Box 12217, Fort Worth, Tex.
John Bemrose, Sohio Petroleum Co., 1300 Skirvin Tower, Oklahoma City, Okla.
George A. Grimm, Tide Water Associated Oil Co., Box 1231, Midland, Texas
B. C. Tucker, Union Producing Co., Box 1407, Shreveport, La.

AEC OPENING FOR GEOPHYSICIST

The Atomic Energy Commission has requested SEG to announce an opening in Denver, Colorado, for a graduate geophysicist or physicist. The duties involve development, modification, testing, and evaluation of geophysical techniques for applicability to uranium. The salary will range from $6390 to $8645. Address inquiries to U. S. Atomic Energy Commission, Grand Junction Operations Office, Grand Junction, Colorado.

NEW HEADQUARTERS FOR THE AMERICAN INSTITUTE OF PHYSICS

On October 21, 1957, a number of distinguished scientists and educators gathered in New York City for the dedication of the new headquarters of the American Institute of Physics at 335 East 45th Street, in the immediate neighborhood of the United Nations headquarters. This new structure, providing three times the amount of space that was available at the old headquarters, will facilitate the work of the Institute whose staff in the past fourteen years has grown from twenty-five to sixty-five and whose membership has more than doubled.

The Institute is actually a federation of five professional physical societies, and it is concerned primarily with the advancement and publication of physical research, the most important result of which is the annual appearance of over 19,000 pages of literature.

These ceremonies also provided occasion for the establishment of two memorials to the late Dr. Karl Taylor Compton who was one of the founders of the AIP and the first chairman of its Governing Board. The Karl Taylor Compton Memorial Room was dedicated, and the first Karl Taylor Compton Gold Medal for distinguished service in physics was awarded to Professor George B. Pegram of Columbia University.

NEW DEVELOPMENTS IN THE NAS-NRC OFFICE OF CRITICAL TABLES

A communication from President Detlev W. Bronk, of the National Acacemy of Sciences-National Research Council, will be of great interest to all physicists, chemists, and engineers who have been concerned over the obsolescence of the International Critical Tables.

On October 7, 1957, Dr. Guy Waddington, a physical chemist of international repute, assumed the directorship of the Office of Critical Tables in the Division of Chemistry and Chemical Technology. A major function of this office will be to coordinate several data compilation projects now in progress and to maintain an index of available tables and a directory of these projects to assure the ready availability of scientific numerical data to American science and industry.

By January 1, 1958, an Advisory Board on Critical Tables will have been established with fifty or more members representing the various governmental agencies and scientific and technical organizations having interests in critical data compilations.

All of this is good indication that more up-to-date material will be available in the near future to supplement the invaluable work done from 1926 to 1933 under the auspices of the NAS-NRC.

NEW LABORATORIES FOR NEWMONT

This insert shows the new geophysical and metallurgical laboratories of Newmont Exploration Ltd., located on Briar Ridge Road between Danbury and Ridgefield, Connecticut.

This is one of the first laboratories ever built for mining geophysical development. Since 1947, however, when it initiated use of the overvoltage method, Newmont has been actively engaged in mining geophysics.

IRE INAUGURATES AFFILIATE PLAN

The Board of Directors of the Institute of Radio Engineers has recently adopted a plan which will permit qualified non-IRE members to become affiliated with certain of the IRE professional groups without first joining the IRE itself.

In connection with this plan, it is now possible for members of the Society of Exploration Geophysicists to join the IRE professional group on instrumentation as "affiliates." This group issues a quarterly journal devoted to new electronic measurement and instrumentation techniques, sponsors national meetings during the year, and has local chapters in Atlanta, Chicago, Houston, Long Island, and Washington, D. C. These services are available to affiliates for a fee of $5.50 per year.

Further information may be obtained by writing to the Institute of Radio Engineers, Inc., 1 East 79th Street, New York 21, N. Y.

STAFF CHANGES AT M.I.T.

The following staff changes have taken place in the Department of Geology and Geophysics at M.I.T. Walter L. Whitehead retired last June but continued as director of the 1957 M.I.T. Summer School of Geology at Crystal Cliffs, Nova Scotia, and has been appointed lecturer in geology at M.I.T. and visiting professor at St. Francis Xavier University, Antigonish, Nova Scotia. Herbert E. Hawkes resigned to accept a professorship in the division of mineral exploration, University of California (Berkeley). William S. von Arx and J. Brackett Hersey, physical oceanographers at Woods Hole Oceanographic Institution, have been appointed associate professors and will again offer a lecture course in Physical Oceanography at M.I.T. as well as supervising graduate thesis work of M.I.T. students at Woods Hole. Arthur J. Boucot, formerly geologist with the U. S. Geological Survey and last year a Guggenheim Fellow in Europe, joined the staff as assistant professor of geology. He will offer work in paleontology and sedimentology and direct the M.I.T. summer school of geology. Harry Hughes, scientific officer, United Kingdom Atomic Energy Authority, is visiting lecturer in geophysics during the present school year while Stephen M. Simpson, Jr., assistant professor in geophysics, is on leave. James C. Savage has been appointed lecturer in geophysics, Theodore R. Madden will continue as lecturer, and Norman H. Haskell as research associate.

In the Department of Meteorology, Norman A. Phillips has been appointed associate professor and Lewis D. Kaplan has joined the staff after returning from a year at Imperial College, London. Dr. Phillips recently received the Napier Shaw Memorial Prize of the Royal Meteorological Society for his paper, "The General Circulation of the Atmosphere: A Numerical Experiment," and will continue his pioneering work in this area. Dr. Kaplan will continue his fundamental research on long-wave radiation in the atmosphere.

These staff changes and additions in the departments of Geology and Geophysics and of Meteorology are in line with a long-range plan to develop at M.I.T. an integrated program of instruction and research in all of the earth sciences.

PERSONAL ITEMS

RICHARD BREWER has joined the firm of C. B. Reed and Associates which maintains offices in Austin and Fort Worth, Texas, and Washington, D. C.

GEORGE H. ZWIEBEL, JR., has been assigned to Tripoli, Libya, as seismic party chief for Namco International, the foreign operations affiliate of the National Geophysical Company, Inc. Mr. Zwiebel has been with National Geophysical for nearly eleven years. His new address is:

c/o Namco International
P.O. Box 677
Tripoli, Libya

VICTOR VAQUIER, formerly professor of geophysics at the New Mexico Institute of Mining and Technology, is now research geophysicist at the Scripps Institution of Oceanography, University of California, La Jolla, California. His new address is:

Marine Physical Laboratory
San Diego 52, California

The name of the geological and geophysical firm of Johnson and Straley has been changed to H. W. Straley, with offices in the Seneca Trail Building, Princeton, West Virginia. The firm's business activities and personnel, except for the late Mr. W. R. Johnson, Jr., will remain the same.

ALBERT P. CRARY is leading a group of five IGY scientists and two Navy men who planned to leave Little America on October 24 on the first leg of a 1,500-mile Antarctic traverse, Dr. Laurence M. Gould, Director of the US-IGY Antarctic Program, has announced. Their departure, which was scheduled for October 22, was delayed because of near blizzard weather.

The traverse, the first of several to be undertaken by IGY scientists during this year's IGY Antarctic program, was to cover the Ross Ice Shelf as far as McMurdo Sound then swing south up to the Beardmore Glacier, and return to Little America. The area covered by the traverse is roughly comparable to that of California.

The purpose of the traverse, Dr. Gould said, is to gather detailed information about the formation and present character of the floating ice sheet that makes up the Ross Ice Shelf as well as to determine ice thicknesses and water depth by seismic methods.

Ice surface elevation will also be determined.

Other measurements will be made of the earth's magnetic field strength and magnetic compass variations. Gravity studies will be made throughout the traverse, as will meteorological measurements of temperature, pressure, humidity, and wind, and wind drift patterns. The party will also survey mountain peaks and ranges along the route of the traverse.

Appointment of ROBERT W. OLSON as vice president-research and engineering of Texas Instruments Incorporated, and E. O. VETTER as general manager of TI's Industrial Instrumentation division at Houston, was announced by P. E. HAGGERTY, executive vice president.

Expansion of Latin American operations of Geophysical Service Inc. has prompted several appointments in supervisory personnel for that area, announced GSI vice president J. W. Thomas.

Thomas in charge of Latin American operations for the Dallas-based petroleum exploration firm, said G. J. Kohler, Jr., has been named manager of Latin American operations. Reporting to Kohler will be four regional operations managers.

Rodolfo Martin will direct GSI operations in Mexico from Mexico City. John Donna is supervisor for the area. C. J. Spivey will remain in Caracas as manager of Venezuelan operations. P. S. Stoutjesdyk, in Rio de Janeiro, will manage Brazilian operations. H. L. Heggy and P. E. Swensen will be supervisors in Brazil. GSI's Andean operations will be managed from Lima, Peru, by D. W. Rockwell, with Murrell Holbert as supervisor in Bogota, Colombia.

Thomas said the appointments were made in order to assure GSI field parties of continued "on-the-ground" supervision during their operations in Latin America. Further appointments are to be made shortly in Bolivia and Guatemala.

V. L. JONES, 1412 South Norfolk, Tulsa, Okla., has the following issues of GEOPHYSICS for sale:

v. 14, nos. 1, 2, 3, & 4; v. 15, nos. 1, 2, 3, & 4; v. 16, nos. 1 (2 copies), & 2.

FIELDING MITCHELL, Box 120, Denver, Colorado, would like to obtain copies of the following issues of GEOPHYSICS:

v. 7, nos. 3 & 4 (July & October, 1942); v. 10 nos. 2 & 4 (April & October, 1945).

He has a few numbers of GEOPHYSICS for the years 1946 to 1949 which he would trade for the above issues.

LT. (j.g.) ROBERT E. MACDOUGAL, USN, and Miss GAYLE HONE, both formerly associated with the Columbia Geneva Steel Co., Provo, Utah, were married in San Francisco on June 29, 1957.

HENRY C. CORTES died December 6, 1957 in Honolulu, T. H. Services were held in Dallas December 12, with interment December 14 on the campus of University of the South, Sewanee, Tennessee. Mr. Cortes was to have retired as vice president and director of Magnolia Petroleum Co. January 1, 1958. He was president of the SEG in 1945–46, and initiated the Geophysical Case Histories series of the Society. A memorial to Mr. Cortes will appear in the April 1958 issue of GEOPHYSICS. The family has requested that any remembrances be in the form of contributions to The Chapel Fund, University of the South, Sewanee, Tennessee.

CALENDAR OF MEETINGS

1958

February

16–20 American Institute of Mining, Metallurgical, and Petroleum Engineers, Annual Meeting, Hotel Statler, New York City

March

3–4 American Institute of Mining, Metallurgical, and Petroleum Engineers, 4th Annual Joint Meeting of Rocky Mountain Petroleum Sections, Cosmopolitan Hotel, Denver, Colorado

10–13 American Association of Petroleum Geologists, 43rd Annual Meeting, Biltmore Hotel, Los Angeles, California (E. Harold Rader, Standard Oil Company of California, 605 W. Olympic Blvd., Los Angeles 15, California)

20–21 American Institute of Mining, Metallurgical, and Petroleum Engineers: Society of Petroleum Engineers, Reservoir Engineering Symposium, Mid-Continent Section, Mayo Hotel, Tulsa, Oklahoma

23–29 American Society of Photogrammetry, Annual Meeting, Shoreham Hotel, Washington

27–29 Optical Society of America, Spring Meeting, Sheraton-Park Hotel, Washington

April

14–16 Canadian Institute of Mining and Metallurgy, Annual General Meeting, Hotel Vancouver, Vancouver, B. C.

17–18 American Institute of Mining, Metallurgical, and Petroleum Engineers, La.-Ark., East Texas and Miss. Petroleum Sections, Gas Technology Symposium, Shreveport, Louisiana

17–18 Society of Exploration Geophysicists, Eleventh Annual Midwestern Meeting, Tulsa, Oklahoma (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

27–30 American Association of Petroleum Geologists, Rocky Mountain Section, Casper, Wyoming

October

13–16 Society of Exploration Geophysicists, 28th Annual Meeting, Hotel Gunter, San Antonio, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1959

March

16–19 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, National Convention, Memorial Auditorium, Dallas

November

9–12 Society of Exploration Geophysicists, 29th Annual Meeting, Biltmore Hotel, Los Angeles, California (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1960

February

25–28 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, National Convention, Chalfonte-Haddon Hall, Atlantic City

November

7–10 Society of Exploration Geophysicists, 30th Annual Meeting, Moody Convention Center, Galveston, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1961

April

24–27 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, National Convention, Municipal Auditorium, Denver

November

5–9 Society of Exploration Geophysicists, 31st Annual Meeting, Denver, Colorado (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

* * * * *

July 1, 1957 to December 31, 1958

International Geophysical Year (Worldwide) *vide* GEOPHYSICS, v. 21, p. 257–259, and v. 21, p. 681–690 (H. Odishaw, National Academy of Sciences, Washington 25, D. C.)

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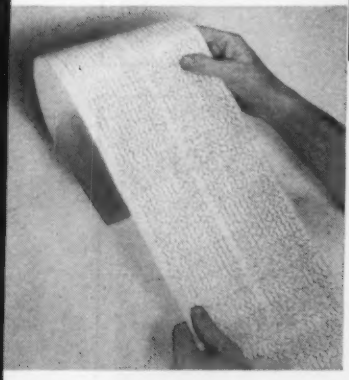

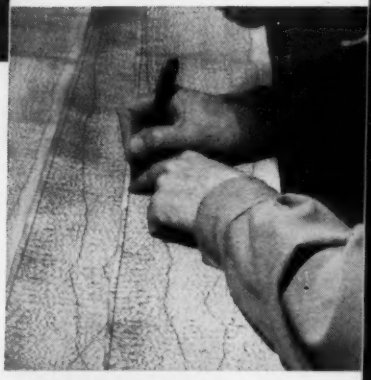

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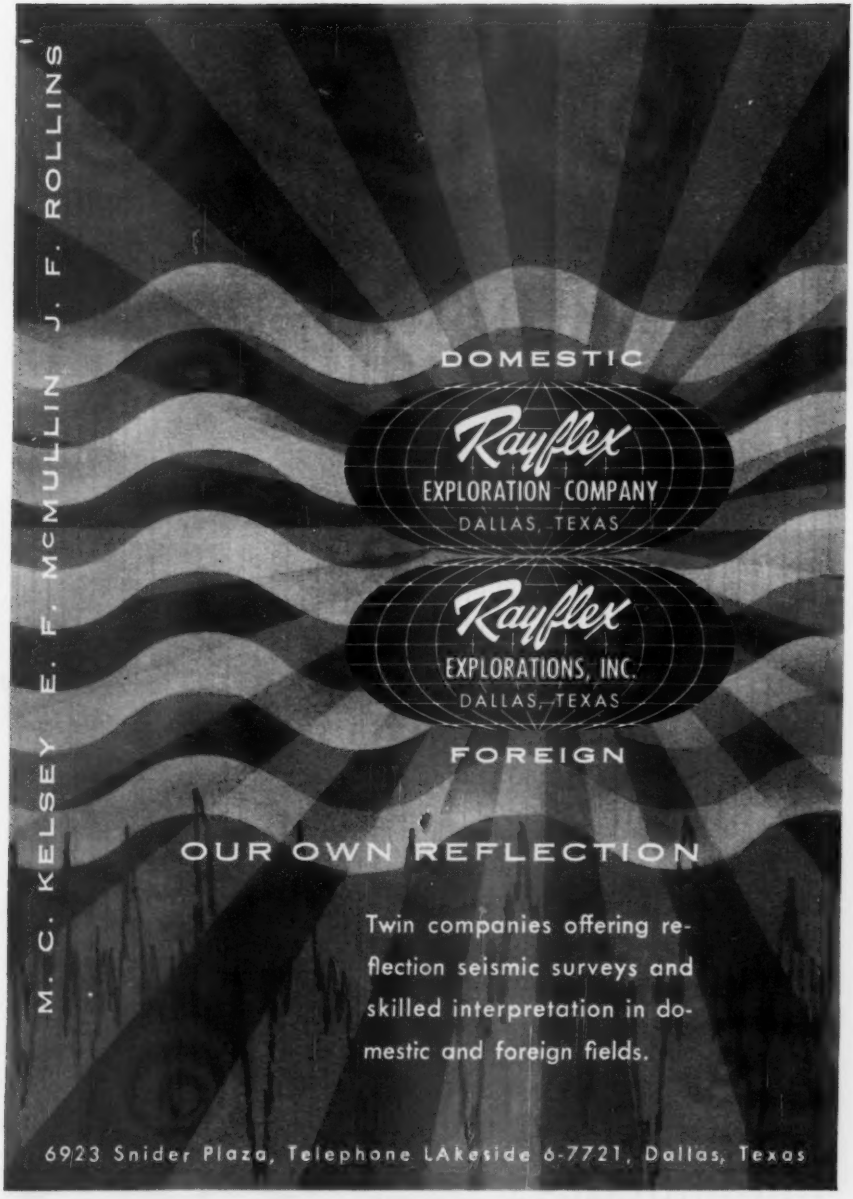
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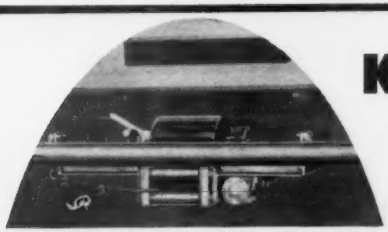

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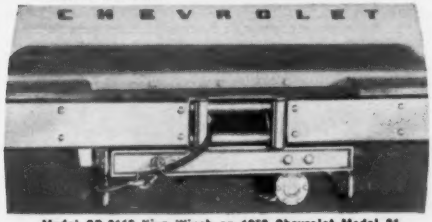

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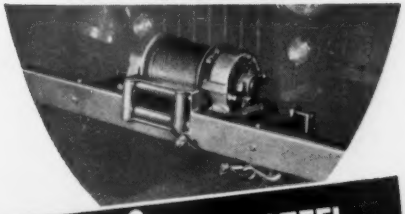

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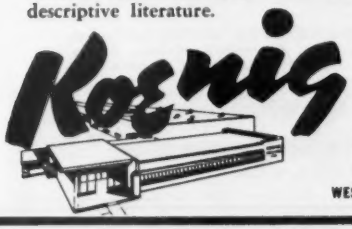

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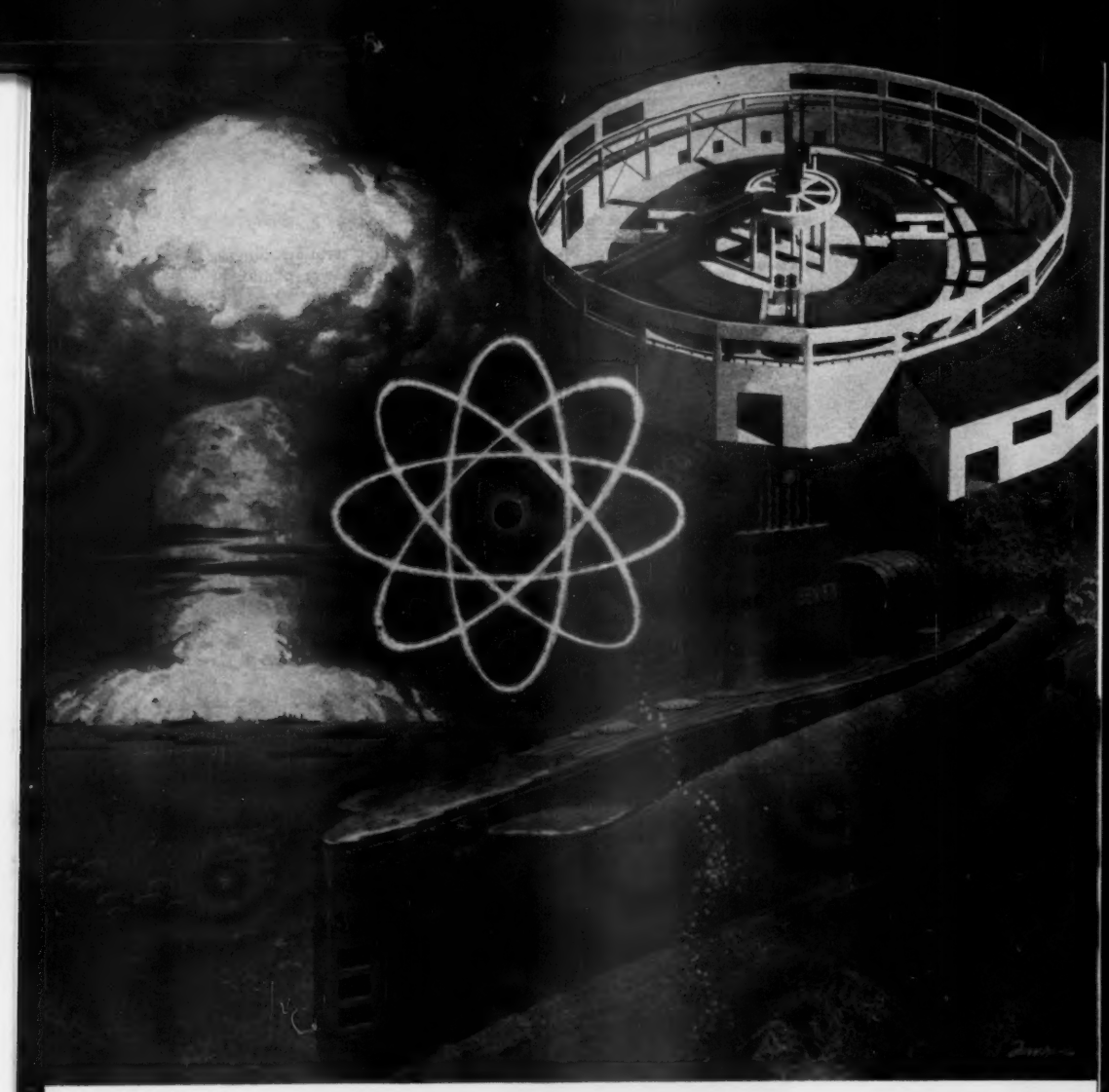

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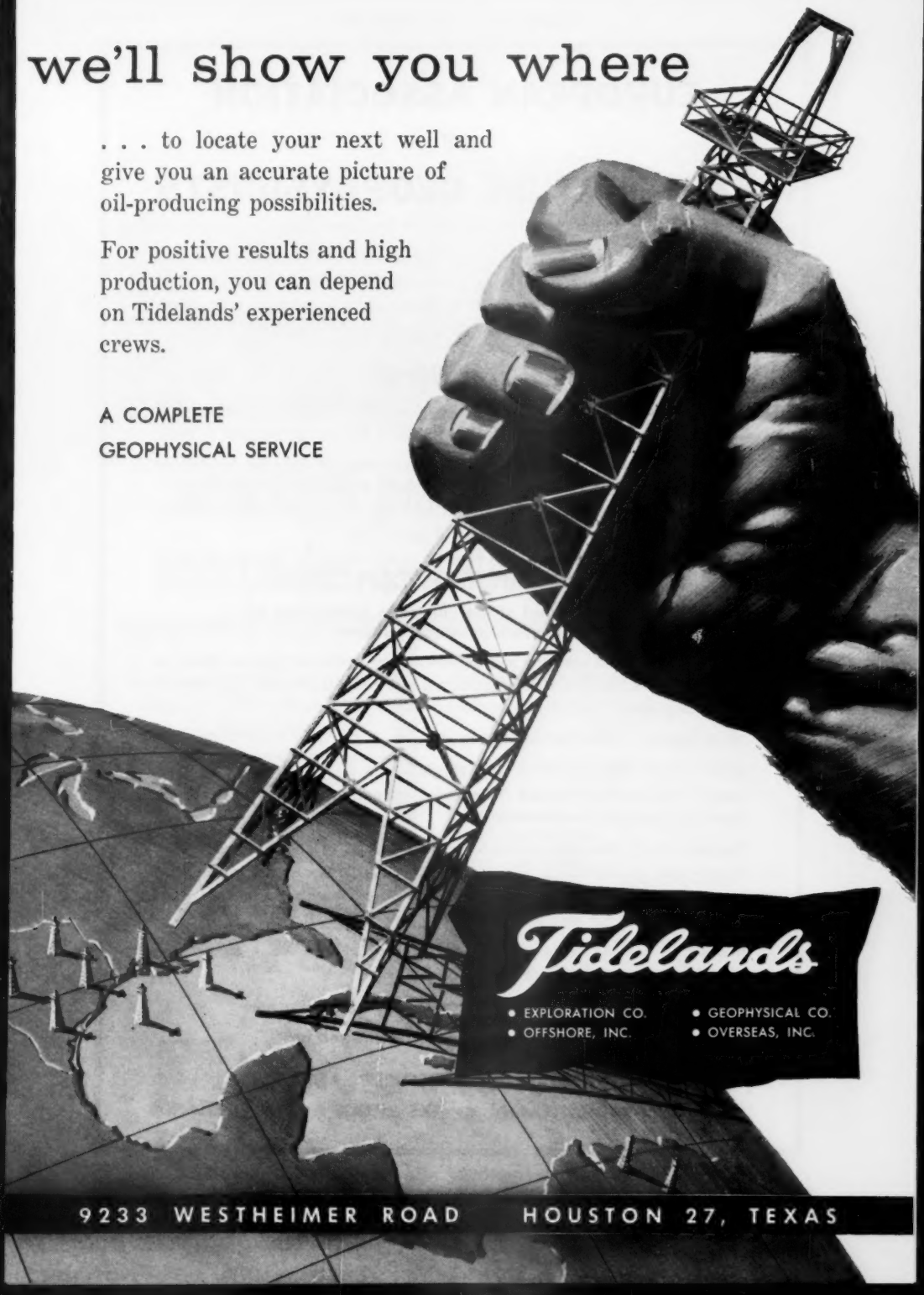

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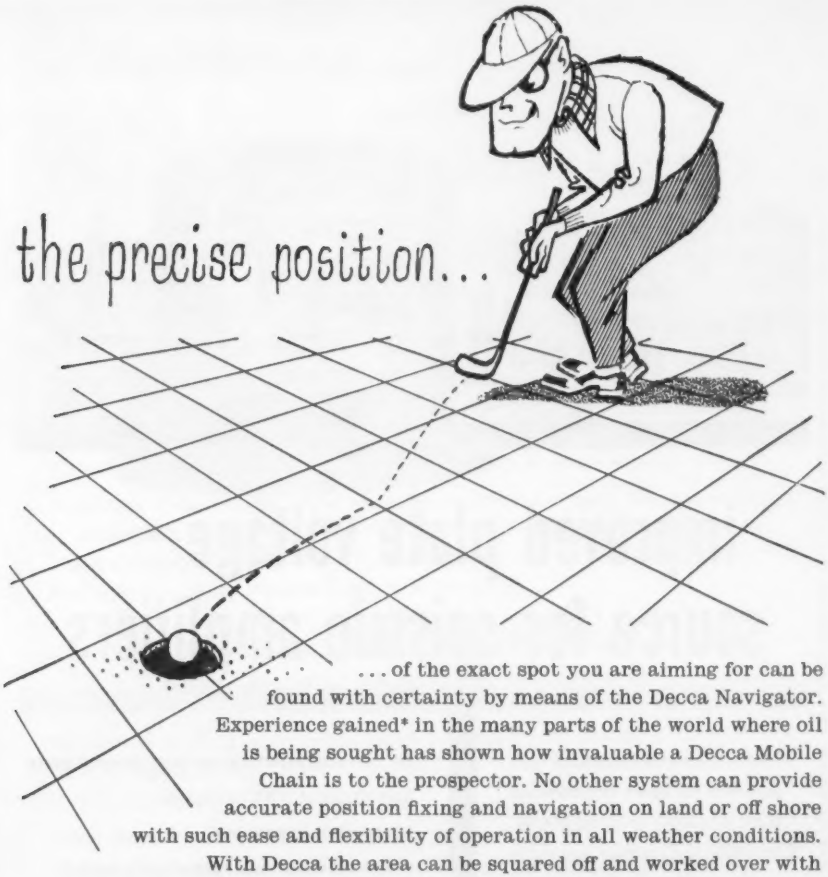

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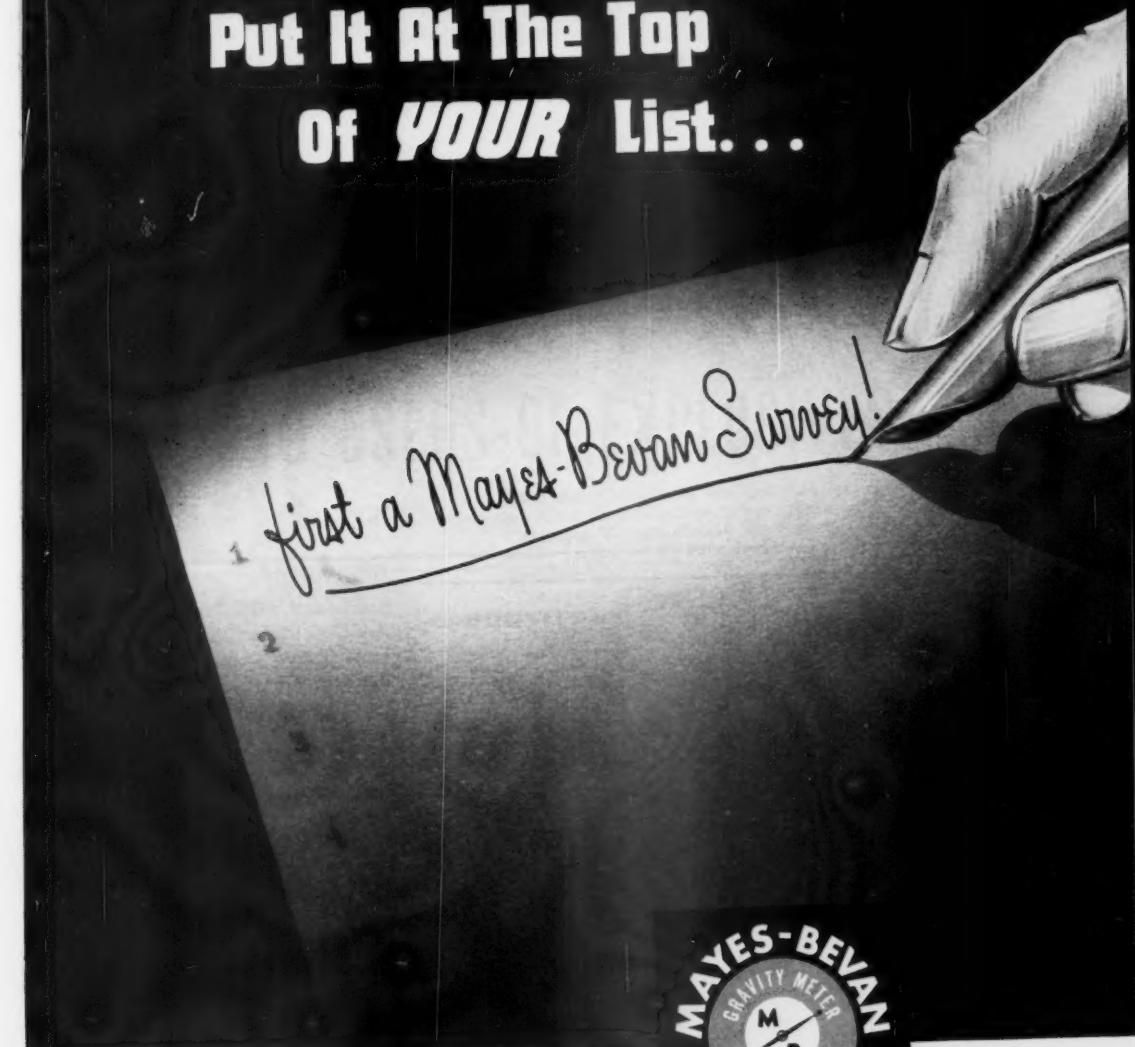

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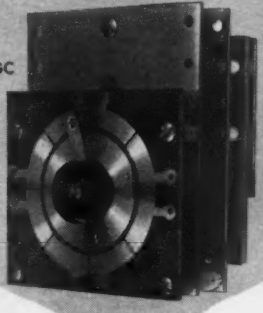

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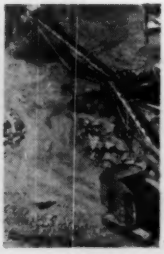
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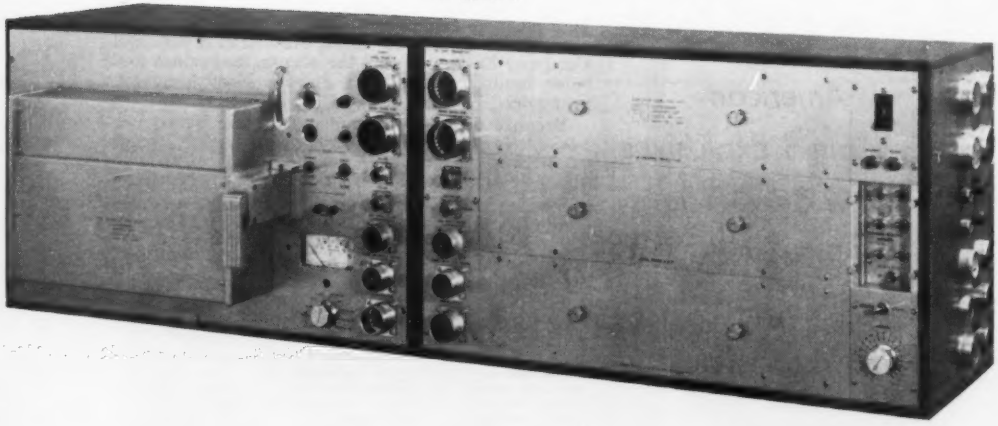

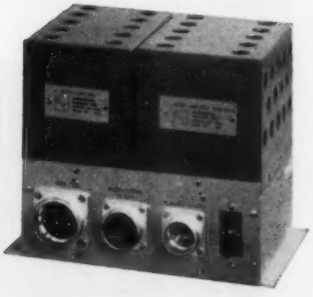

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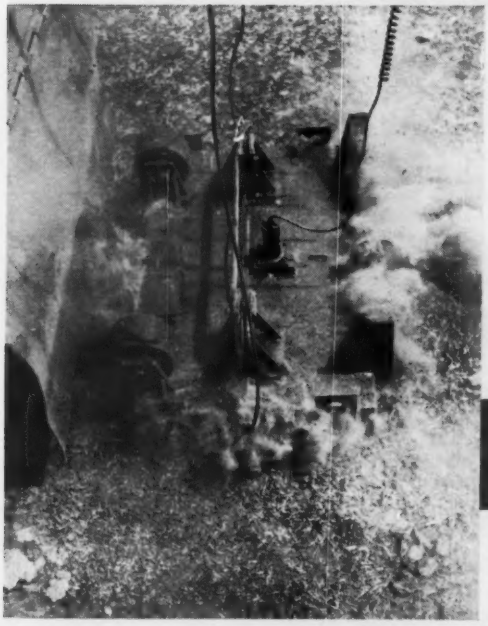

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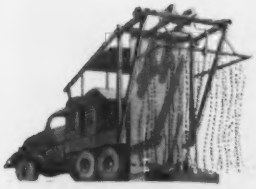

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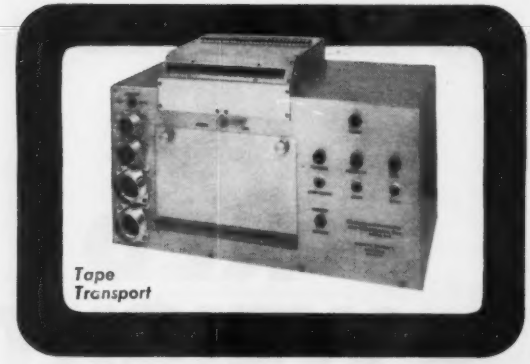

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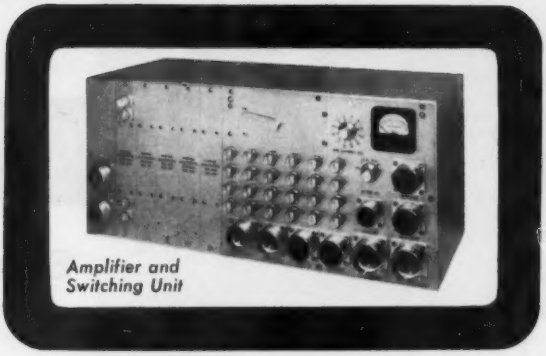

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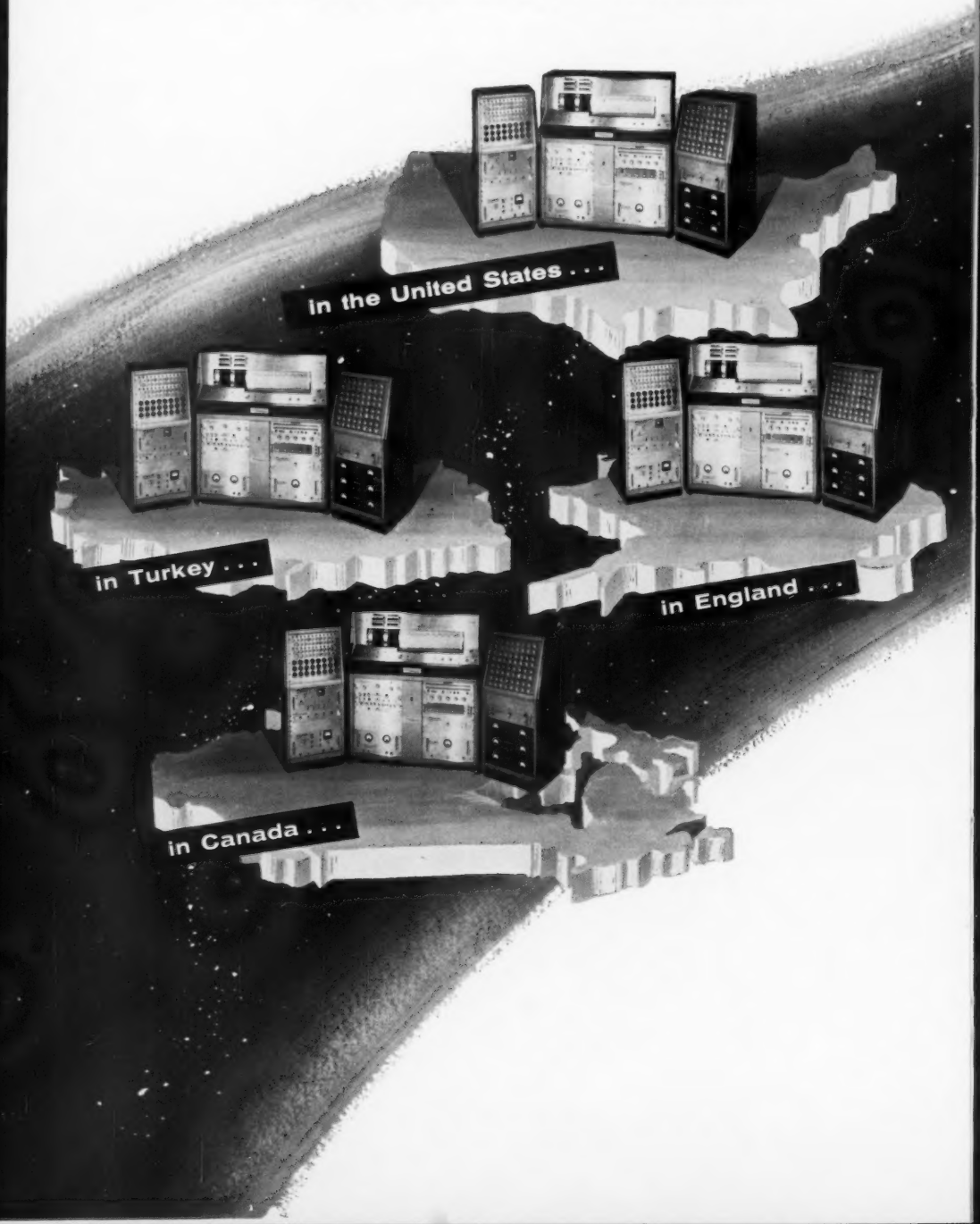

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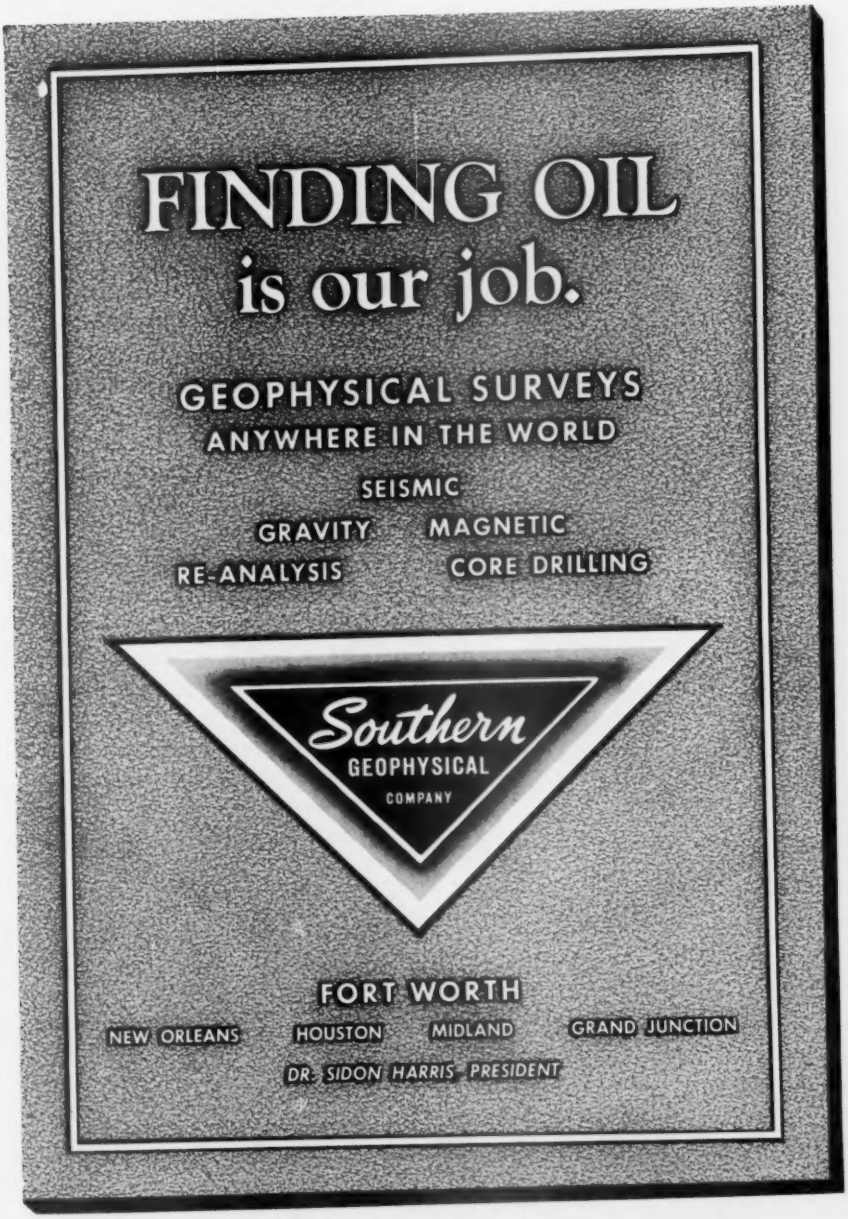
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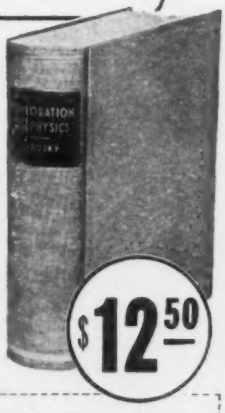

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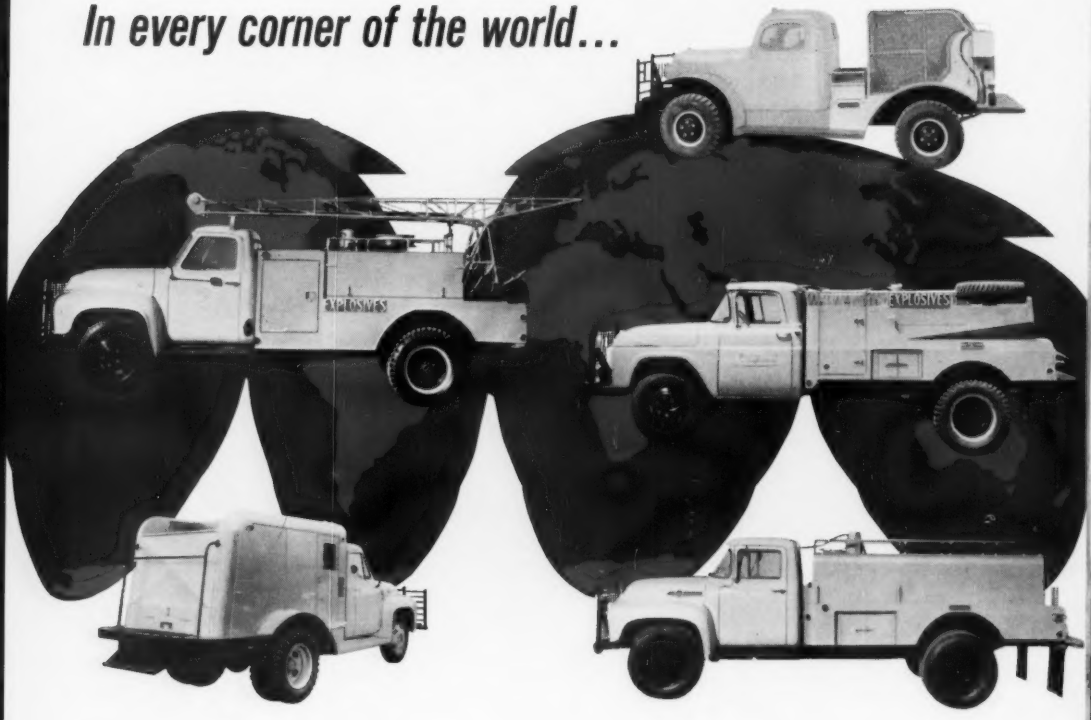

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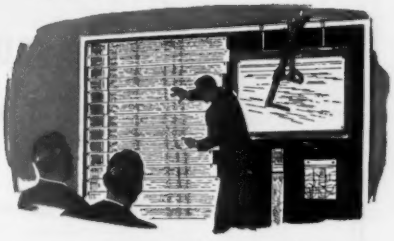

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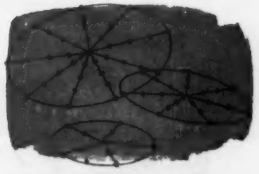

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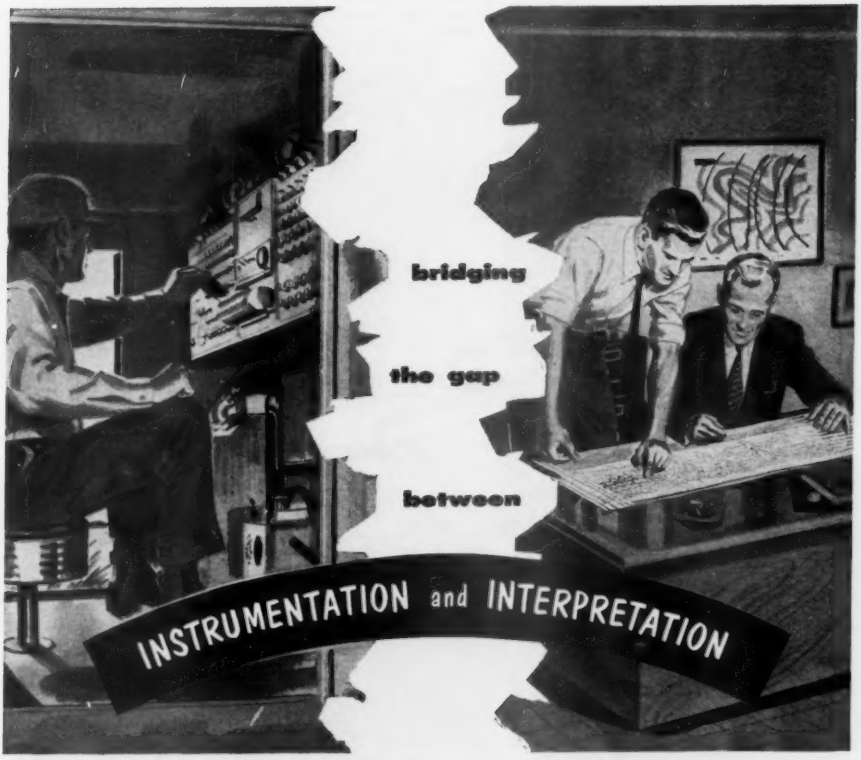

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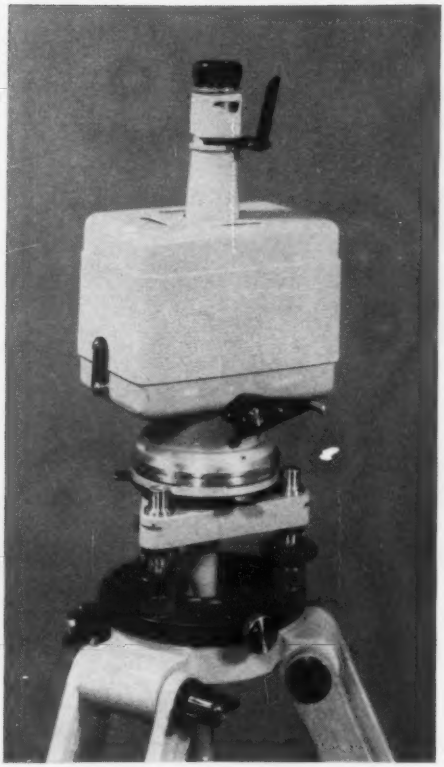

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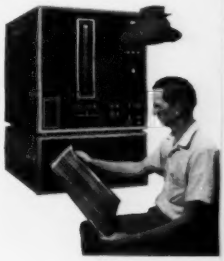
History of the Seismograph
Number 5 in a series.

Beginning of an Industry -- *the first reflection seismograph party*

During the summer of 1917, Drs. J. Clarence Karcher and William P. Haseman first discussed the possibility of utilizing reflected sound waves to determine the location of likely oil-bearing structures. On April 12, 1919, Dr. Karcher made the first land reflection seismograph record in a rock quarry near the National Bureau of Standards building in Washington, D. C.

Later a company was organized to pursue the development of the reflection method of prospecting. Equipment was completed in May of 1921 and on June 4, 1921, the first seismic field party, led by Karcher, conducted experiments in a creek bed one and one-quarter miles due west of Belle Isle, a suburb of Oklahoma City. Experiments continued in other parts of Oklahoma through 1921 and some basic techniques were developed which are still in use, such as that of covering the dynamite with a column of water to increase its efficiency in producing seismic waves. The method was put to practical use in oil exploration in 1925 when the Geophysical Research Corporation was organized as an Amerada subsidiary with Dr. E. L. DeGolyer as president, Dr. Karcher as general manager, and Eugene McDermott as laboratory director. In 1929 Karcher sold his interest in G.R.C. and in 1930 with McDermott co-founded Geophysical Service Inc., the first independent geophysical service to specialize in reflection seismograph surveys. This organization is now Texas Instruments, and G.S.I. is its petroleum exploration subsidiary.

To date, the reflection seismograph has not been bettered as a geophysical method and the finest instrumentation available are the *Seismation* systems developed by Texas Instruments —the 7000B "All Purpose" Seismograph, magneDISC, seisMAC, VIP Variable Intensity Plotter, and SAC Seismic Analog Computer.



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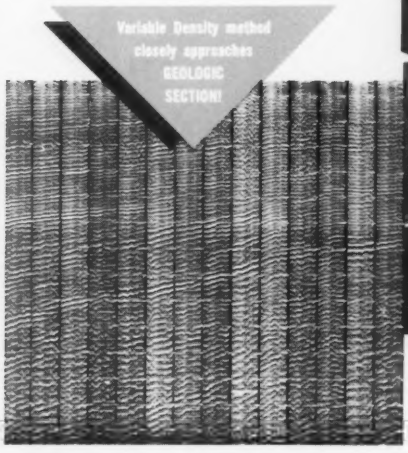

The VARIABLE INTENSITY PLOTTER developed by Texas Instruments rapidly corrects for time or depth and compresses a mass of seismic data into section form, while preserving the relative character and contrast of recorded events. The VIP cross section closely approaches a geologic section, and is therefore readily comprehended by non-geophysical personnel.

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History of the Gravity Meter
Number 5 in a series.

Development of the first gravity meter for prospecting

In 1918, Gustaf Ising announced the principle of using a highly *astatised* pendulum, turning around an elastic horizontal axis, as a convenient means for making relative gravity measurements. This was to be accomplished, either dynamically by observing the time of swing, or statically by observing the equilibrium deflections of the pendulum from its vertical position.

Ising, with the assistance of N. Urelius and later T. Eeg-Olofsson, developed several astatised elastic pendulum meters of the static type. P. Lejay and F. Holweck also employed astatised pendulums, using only the dynamic method. The instrument illustrated here is a refinement of earlier types and was constructed for the Electrical Prospecting Company in 1936.

Two difficulties of the astatised pendulum are the temperature variation of the modulus of elasticity of quartz, and the sensitivity of the pendulum to accidental tilting of its foot. The first was overcome by surrounding the pendulum with two compartments containing melting ice (1 and 2). The second was corrected by containing the pendulum in hermetically sealed chamber (3) suspended by metal bands (4) with weight in oil-damping chamber (6), all contained in waterproof compartment (5). The degree of astatisation may be measured two ways: 1. the micrometer screw method which brings the pendulum to coincide with fixed lines and notes the corresponding positions of the screw; and 2. the load method causing the pendulum to make symmetrical deviations to each side of its zero position—the latter is usually recorded by photographic attachments. Field reading time with this instrument was 30-40 minutes, and its accuracy approximately .5 milligal.

The Worden Gravity Meter, today's world standard, requires no external power source. Temperature changes are compensated internally, weight only 5⅛ pounds, with reading accuracy of 0.01 milligal. Write for Bulletin GM-204 on the rugged Worden!

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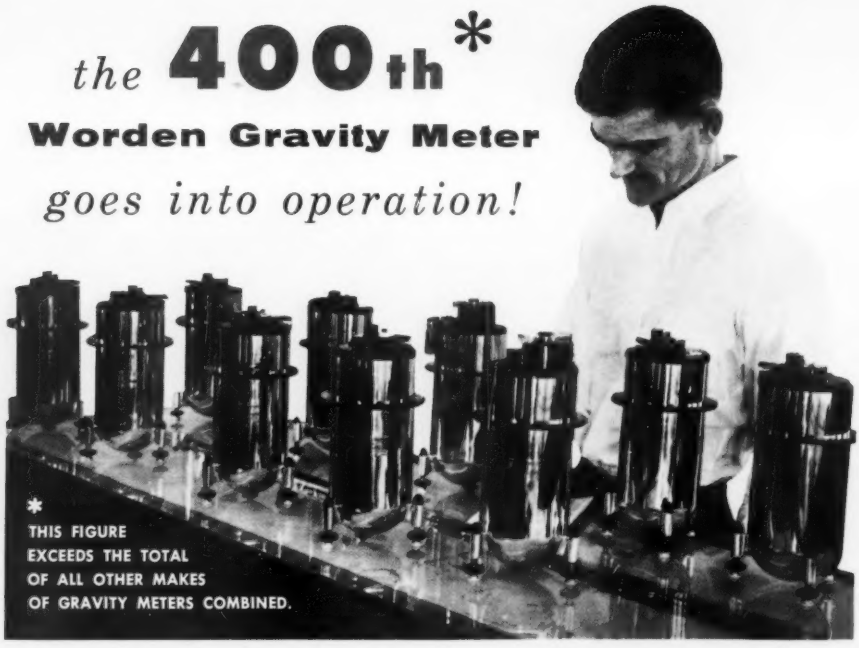
the 400th* Worden Gravity Meter *goes into operation!*



* THIS FIGURE EXCEEDS THE TOTAL OF ALL OTHER MAKES OF GRAVITY METERS COMBINED.

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The Worden Gravity Meter weighs only five pounds—1/4 to 1/5 the weight of other gravity meters in use. The elastic system of the meter is quartz with basic mass of only five milligrams, and is sealed in a partial vacuum. Internally compensated, no external power source or heating coils are required for operation in any temperature. The Worden Meter does not require pampering or clamping between stations and will maintain its high accuracy under the roughest of expected operating conditions.

For further information on Worden Standard and Geodetic Gravity Meters, write for Bulletin No. GM-204.

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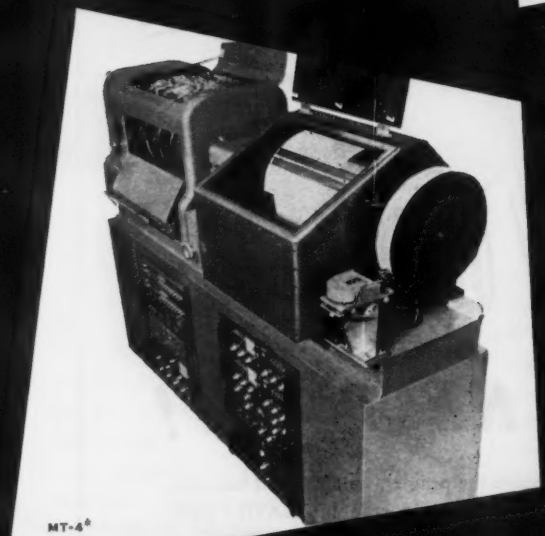

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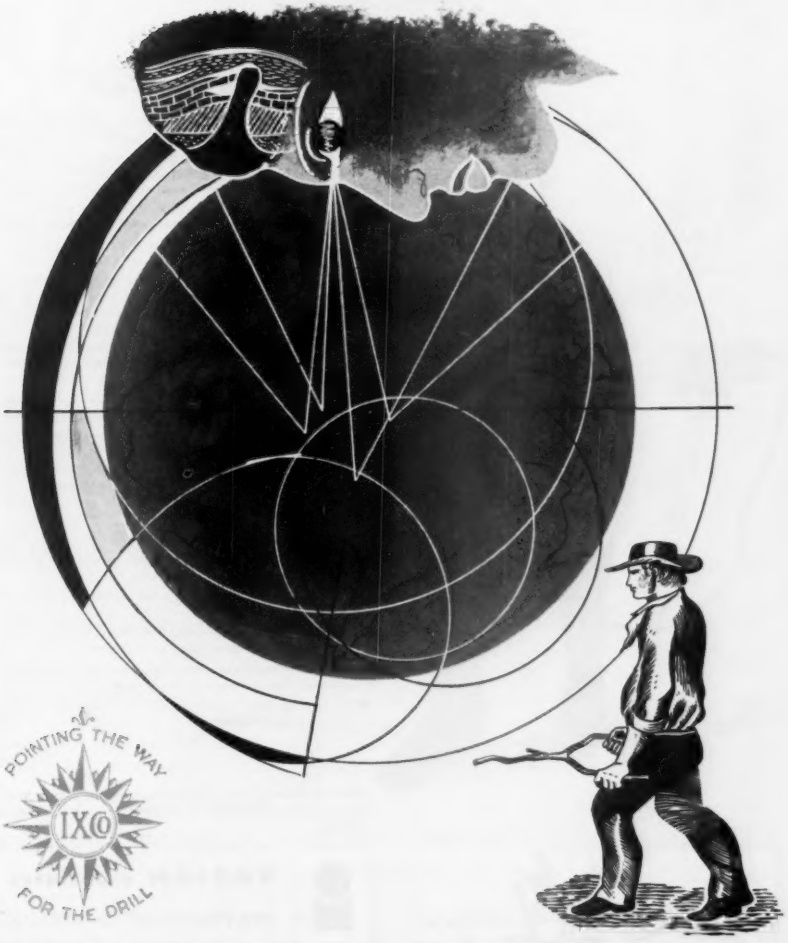

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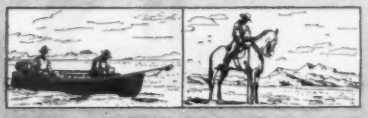

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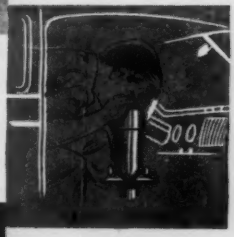

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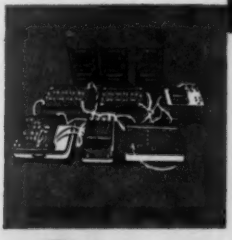

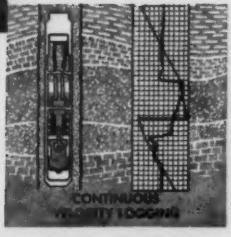

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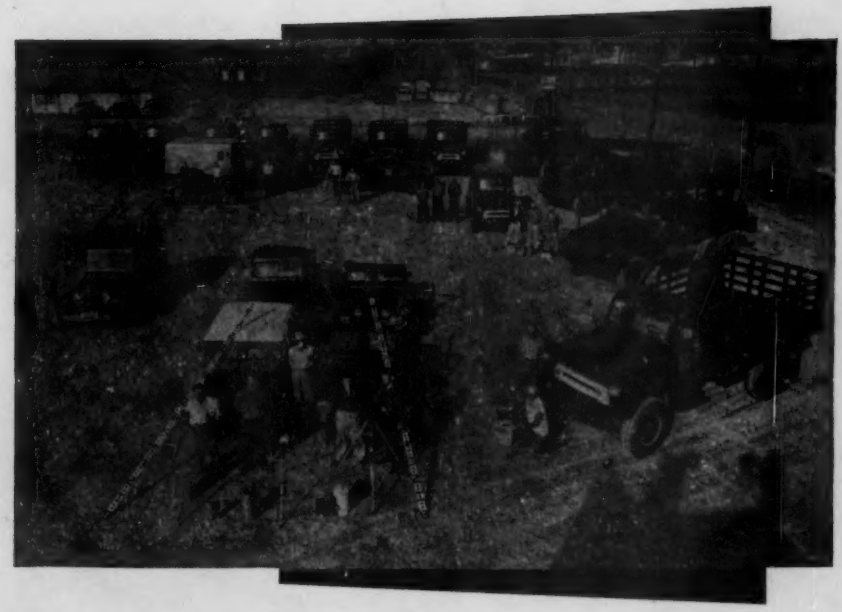

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